EDDY CURRENT EVALUATION OF ELECTRICAL ANISOTROPY IN POLYCRYSTALLINE TI-6AL-4V

Mark Blodgett
Metals, Ceramics, and NDE Division
Air Force Research Laboratory (AFRL/MLLP)
Wright-Patterson Air Force Base
Dayton, OH 45433

Peter B. Nagy
Department of Aerospace Engineering
University of Cincinnati
Cincinnati, OH 45221

INTRODUCTION

High strength titanium alloys find a significant number of applications throughout the aircraft industry for gas turbine engine and airframe components. Ti-6Al-4V is an alloy that has been around since the 1950's and has been used extensively for fan blades, disks, and superplastically formed and diffusion bonded structures. This alloy has been studied and tested in virtually every conceivable way and a great deal is known about the material in terms of its capabilities, yet there are still lingering performance issues that evade researchers. A recent initiative by the Air Force to better understand conventional Ti alloys from the standpoint of High Cycle Fatigue (HCF) has brought to light some intriguing research in the nondestructive characterization of polycrystalline titanium alloys. The major goal of this research is to detect and characterize the microscopic defects or fatigue damage precursors associated with HCF and to understand some of the physical characteristics of the nucleation and growth of low-level, mechanically imparted damage. From a nondestructive inspection viewpoint the goal boils down to finding and interpreting signals from smaller and smaller "defects." With this approach, the identification of smaller defects early in the service life of the component presumably leads to higher reliability of the aircraft through the removal of flawed components for rework, scrap, or further study.

One of the problems encountered in the study of Ti-64 involves understanding the role of texture and grain structure in causing local variations in mechanical properties and in determining what techniques can be used to detect and map these variations. A significant obstacle to detecting and characterizing incipient damage is grain noise, which basically evolves due to random variations in the crystallography of the microstructure.

Review of Progress in Quantitative Nondestructive Evaluation, Vol. 18
Edited by Thompson and Chimenti, Kluwer Academic/Plenum Publishers, 1999

Unfortunately, in a number of alloys, like Ti-64, the microstructural complexity poses significant challenges stemming from its two phase structure with different crystallographic symmetry, density, and stiffness between the alpha and beta phases. The structure of these Ti alloys tends to be significantly affected by the fabrication process. Often, a microstructure will form with features originating from a prior phase state, owing to its allotropic nature, or from other sources, such as, large colonies and macroscopic structures associated with texture and deformation.

MATERIALS CHARACTERIZATION

Electrical anisotropy plays an important role in the structural integrity assessment of polycrystalline titanium alloys from the standpoint of fatigue crack detection and the related issue of microstructural noise. In eddy current inspection of noncubic crystallographic classes of polycrystalline metals the electric anisotropy associated with individual grains produces an inherent microstructural variation or noise that is very similar to the well-known acoustic noise produced by the elastic anisotropy of both cubic and noncubic materials in ultrasonic characterization. The presented results demonstrate that although the electrical grain noise is clearly detrimental in eddy current nondestructive testing for small flaws, it can be also exploited for characterization of the microstructure in noncubic polycrystalline materials such as titanium alloys in the same way acoustic grain noise is used for ultrasonic characterization of the microstructure in different materials.

Elastic anisotropy of single crystals plays an important role in ultrasonic materials characterization of polycrystalline materials. Microscopically homogeneous but randomly oriented individual grains make up a macroscopically isotropic but inhomogeneous medium which produces incoherent wave scattering commonly called "grain noise." While acoustic grain noise has an obvious adverse, often prohibitive, effect on ultrasonic flaw detection [1,2] it can be also exploited for ultrasonic characterization of the grain structure [3-6]. Electric anisotropy exhibited by specific types of crystallographic classes can play a very similar role in electromagnetic testing of polycrystalline metals.

All physical properties relating two first-order tensor quantities are characterized by second-order tensors, the directivity of which can be represented by a symmetric ellipsoid [7,8]. Such properties include electrical and thermal conductivity, thermoelectricity, dia- and paramagnetism, and dielectricity. In the most common cubic system, the ellipsoid degenerates into a sphere and these properties become fully isotropic. However, in noncubic materials the same physical properties are inherently anisotropic. In contrast, elastic material properties relate two second-order tensor quantities therefore they are characterized by fourth-order tensors. As a result, from an elastic point of view, cubic crystals are also anisotropic just like other crystallographic classes.

For a hexagonal crystal like pure titanium and its most common alloys the axial symmetry around the principal direction (the hexagonal axis) allows the directional dependence of the electrical resistivity to be described over the entire space by two orthogonal axes and the directivity can be represented as an ellipsoid:

$$\rho(\phi) = \rho_{\perp}\cos^2\phi + \rho_{||}\sin^2\phi, \tag{1}$$

where $\rho_{||}$ and $\rho_{\perp}$ denote the electrical resistivity in the basal plane (plane of isotropy) and normal to it, respectively, and ϕ denotes the angle between the direction of current flow and the normal of the basal plane. It is readily seen from Eq. (1) that in cubic materials the electrical resistivity is fully isotropic due to the balanced symmetry of the lattice structure, i.e., the resistivity becomes a single scalar value and the ellipsoid describing its directional dependence degenerates to a sphere. For eddy current measurements of electrical resistivity in a hexagonally symmetric single crystal, the average surface resistivity can be expressed from Eq. (1) as:

$$\rho_s(\theta) = \tfrac{1}{2}[\rho_\perp \sin^2\theta + \rho_{||}(1 + \cos^2\theta)], \qquad (2)$$

where θ denotes the inclination angle between the basal plane and the surface of the specimen. For example, in pure titanium $\rho_\perp = 48\ \mu\Omega\text{cm}$ and $\rho_{||} = 45.35\ \mu\Omega\text{cm}$, i.e., the resistivity is approximately 6% lower in the basal plane than normal to it [9]. Because of the above described averaging effect of eddy current inspection, the actual grain contrast is expected to be 50% lower in eddy current inspection. In titanium, the average resistivity is approximately 3% lower when the basal plane is parallel to the surface than when it is normal to it.

In nondestructive materials characterization, electrical conductivity is usually measured by the non-contacting eddy current method. Neighbor was the first to extend the eddy current method to electrically anisotropic materials and showed theoretically that one can obtain the full conductance tensor from such measurements [10]. Special eddy current coil configurations that allow the simultaneous measurement of electrical conductivity in two principal directions have been developed for texture assessment in plates [11,12]. Just like in the case of elastic anisotropy, the source of electrical anisotropy can be either (i) intrinsic crystallographic anisotropy in single crystals and textured polycrystals or (ii) structural anisotropy caused by oriented reinforcement in composite materials. The latter can be exploited for eddy current assessment of constituent volume fractions in metal matrix composites [13,14]. Grain boundary contributions to the electrical resistivity [15] can cause additional electrical anisotropy in polycrystalline materials with elongated grains aligned in preferred orientation due to thermal or mechanical treatment in the production of the alloy.

In order to assess the feasibility of eddy current materials characterization and flaw detection in structural alloys of noncubic symmetry, we carried out two sets of experiments [16]. First, we used an eddy current probe to measure the directional variation of the electrical conductivity in pure single crystals of aluminum, copper, and cadmium; the former two materials consist of a cubically symmetric crystallographic lattice, the latter one consists of a hexagonally symmetric lattice (unfortunately, titanium single crystals cannot be grown to sizes large enough for accurate eddy current conductivity measurements). Second, we used an eddy current scanner to map the electrical grain noise in Ti-6Al-4V titanium alloy specimens of different microstructures.

SINGLE CRYSTAL EXPERIMENTS

The Al, Cu, and Cd single crystals used in this study were of random orientation. Each specimen was a solid cylinder of approximately 2" length and 0.5" diameter, large enough to section into multiple test samples of varying surface orientation. Eddy current resistivity measurements were taken on the various single crystal sample sets using a Nortec 19e eddy current instrument and a 0.060"-diameter probe at 2 MHz. The fact that the lift-off curve approaches the resistivity curve at an angle in the impedance plane allows the separation of lift-off from resistivity by proper adjustment of the phase angle on the instrument [17]. For each set of samples, the phase angle was set to isolate lift-off to the horizontal direction, the sensitivity was adjusted, and the instrument was nulled. The vertical output from the eddy current instrument, corresponding to the average electrical resistivity, was captured on a digital oscilloscope. With this automated approach, it was possible to statistically analyze the population of average surface resistivity values corresponding to approximately 500 individual measurements for each sample.

The measured data are shown in Figures 1a through c as histograms of the probability distributions of the surface resistivity for various surface crystallographic orientations in the three single crystals. For each set, only three surfaces showing the most extreme differences in average resistivity are displayed. It should be noted that these values in average electrical resistivity are subject to a variety of small experimental errors, including thermal drift from the instrument or sample, probe alignment and an associated probe rocking effect, inevitable thickness and edge effects, etc., hence the variability in the data. These factors were considered during the data collection and efforts were taken to minimize their affects. The data from Figure 1c clearly demonstrates the crystallographic dependence of the electrical resistivity in cadmium representing noncubic materials, as opposed to the lack of separation demonstrated by cubic copper and aluminum. In the cadmium crystal the values of electrical resistivity are $\rho_{\perp} = 8.3\ \mu\Omega\text{cm}$ and $\rho_{||} = 6.8\ \mu\Omega\text{cm}$, a relatively large difference of approximately 22% between the basal plane and the normal to it [8]. Due to the averaging effect of eddy current measurements, the most extreme resistivity separation which could be expected in Cd is approximately 11%. The average resistivity variation present in the randomly cut Cd samples was clearly measurable with a maximum variation of approximately 3% in resistivity. Considering that we did not necessarily find the principal planes of maximum separation, the measured variation is reasonable, and efforts are being made to confirm this data using the actual crystallographic orientation in each sample.

Because of our particular interest in nondestructive testing of high-strength titanium alloys by eddy current methods, a special attempt was made to obtain the same type of data from a pure alpha (hexagonal) phase Ti single crystal. However, due to the inherently small size of the available Ti single crystals, it was not possible to collect data actually representative of the material's electrical resistivity due to edge affects, which tend to diminish the accuracy of the measurements. Moreover, in titanium, the maximum difference in average resistivity is expected to be only about 3%, i.e., only one fourth of the corresponding variation in Cd. Nevertheless, based on the results from the Cd crystal sample, the evidence of electrical anisotropy in noncubic crystalline materials is clearly supported. To further demonstrate this point, Figure 1d shows the probability distribution of the surface resistivity for a Ti-6Al-4V polycrystalline specimen. As expected, there is a significantly wider variation in the resistivity from point to point than on single crystals, which will be shown later to be caused by the relatively coarse grain structure.

EDDY CURRENT SCANNING

Eddy current testing is the most common electromagnetic nondestructive evaluation method and is widely used in the aerospace industry. Small diameter coils combined with a computer controlled scanning mechanism can be readily used for eddy current imaging. The coil impedance is determined by the resistivity of the specimen as measured by the eddy current, which runs parallel to the surface in a concentric circle with the coil. In this way, an eddy current probe measures the average resistivity in a given plane rather than in a given direction. As the probe is moved along the surface, it measures the local average resistivity along the path of the eddy current in the plane of the surface. The resistivity is

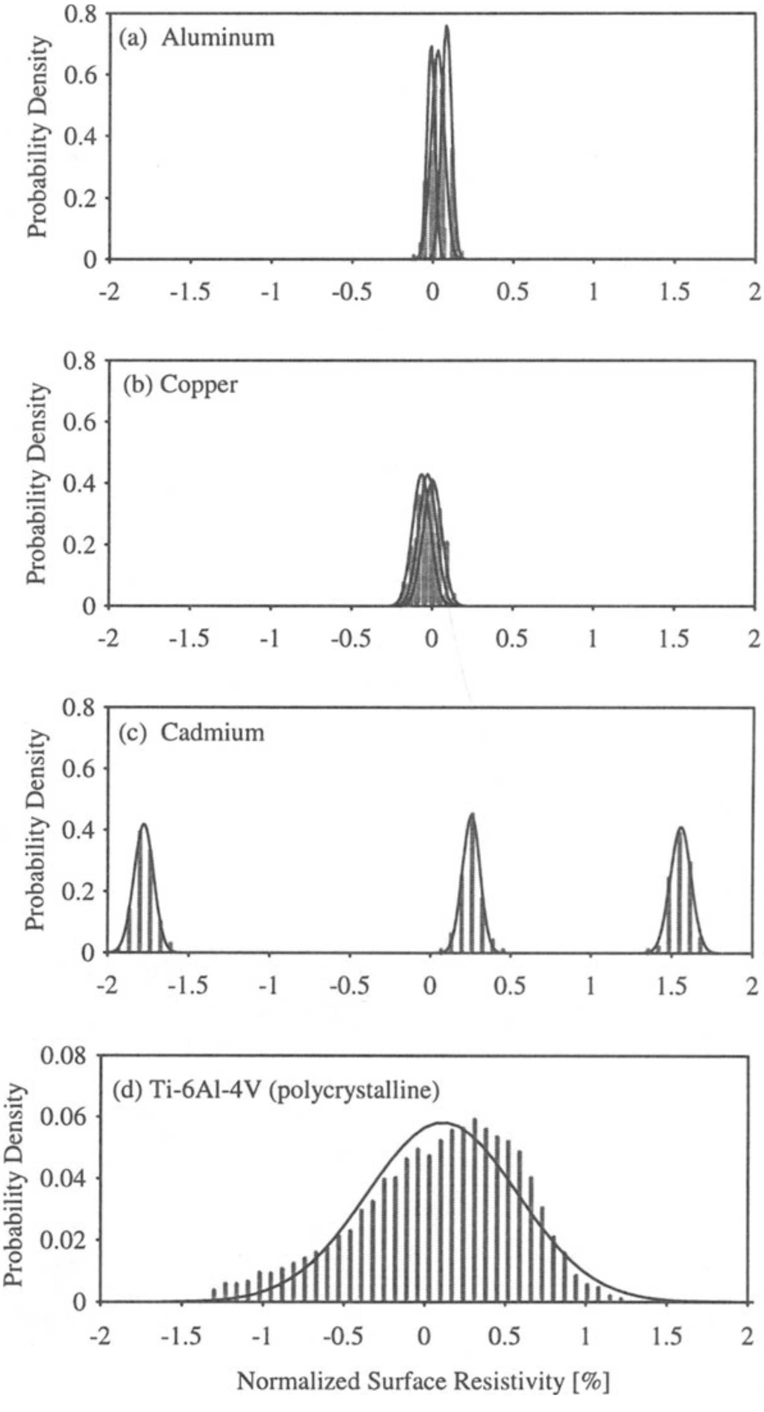

Figure 1. Electrical resistivity probability distributions for three single crystal surface orientations in a) aluminum, b) copper, and c) cadmium and d) on the surface of polycrystalline Ti-6V-4V (solid lines are best fitting Gaussian distributions).

integrated over the entire probe circumference in the eddy current path, resulting in grain contrast that is proportional to the variation of the average electrical resistivity between the different crystallographic planes. This contrast is similar to the mechanical contrast produced by spherical acoustic microscopy, which is determined by the variation of the average surface wave velocity between different crystallographic planes [18].

Two typical eddy current scans of titanium alloy microstructure are shown in Figure 2. Structural alloys of titanium are comprised of microscopically anisotropic grains of random order, which macroscopically behave isotropically. However, often the materials fabrication process results in both small- and large-scale structures which lack the degree of randomness in the crystallites' orientation required to allow the behavior to be fully isotropic. These materials are said to contain texture, which is generally imparted to the material via plastic deformation, like forging. Texture results, for example, in the alignment of like crystallographic slip planes parallel to the rolling plane, while certain slip directions tend to align in the direction of rolling or wire drawing. The development of this preferred orientation also tends to align microstructural features like inclusions, second phase particles, or grain boundaries and texture effects can be observed on a large scale relative to the individually homogeneous grains, often spanning several inches or more. In some polycrystalline titanium alloys, certain microstructural conditions give rise to a highly localized form of crystallographic microtexture causing fractures to preferentially occur along certain weak crystallographic directions [19].

Essentially the same macroscopic inhomogeneity of the microstructure can be observed in polycrystalline Ti-64 via eddy current imaging and acoustic microscopy as shown in Fig. 3 corresponding to a 1"× 1" area on the sample. These images were scanned from a specially heat treated Ti-64 sample to bring about a high degree of grain consolidation to the structure. The large colonies, nominally 2.5 cm, are basically composed of alternating plates of the alpha and beta phases. The principal direction in each of these large colonies is thought to be essentially uniform, thereby forcing the colony to behave as if it were a single crystal. The main reason for generating a sample with such exaggerated structure is to determine if like features could be observed with both eddy

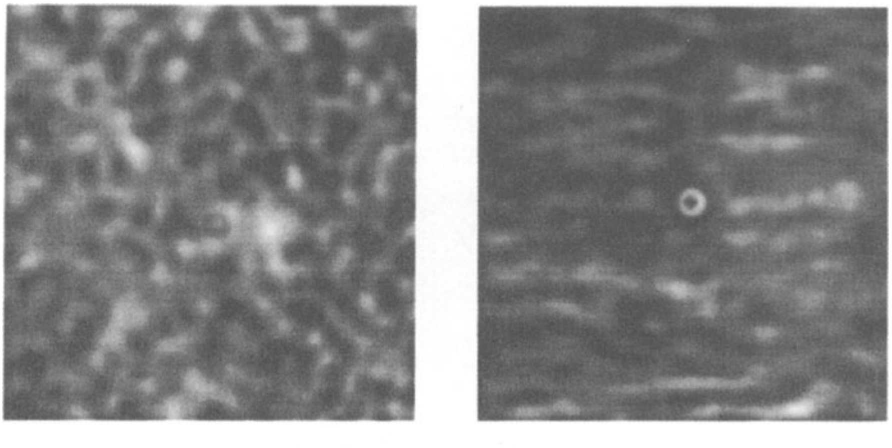
a) b)

Figure 2. Eddy current scans of polycrystalline titanium alloy using a standard 0.060" pancake coil; images are 1" x 1" at 2 MHz. a) An equiaxed, but coarse grained microstructure, and (b) a highly textured billet microstructure (with indentation mark).

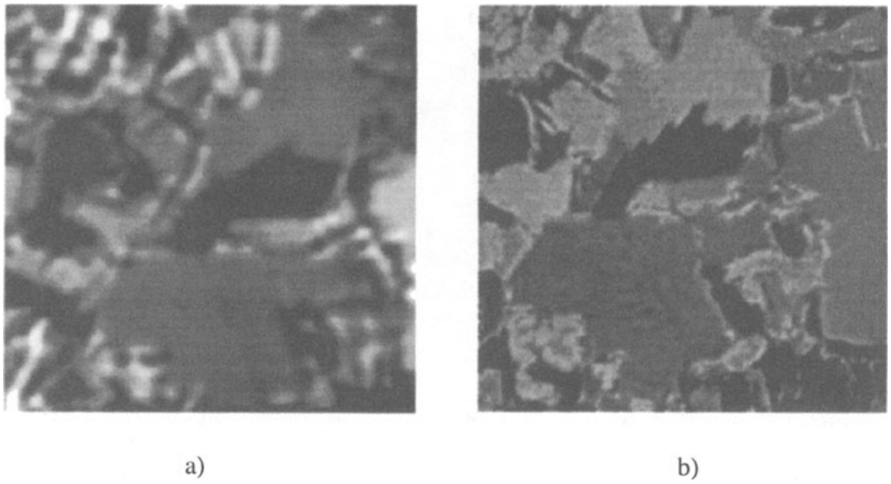
a) b)

Figure 3. A 5 MHz eddy current image (a) scanned over 1" x 1" of a very coarse grained Ti-64 sample and a 40 MHz scanning acoustic microscope image (b) taken over the same region.

current and acoustic scanning techniques. Clearly, the like features do simultaneously appear in the images of Figure 3, due to the relative crystallographic orientation of the various entities encountered during the scan.

CONCLUSIONS

To conclude, some interesting parallels can be observed between the reported electromagnetic approach and conventional ultrasonic evaluation methods. Ultrasonic techniques can be used to exploit the fact that in polycrystalline materials, grain to grain differences in crystallographic orientation and the presence of grain boundaries provide source for scattering of ultrasonic energy. The presence of texture and additional phases of material also play an important role in the ultrasonic response of the material and the scatter provides valuable data which can be used to characterize the microstructural features. In ultrasonic flaw detection, the acoustic grain noise is clearly detrimental due to reduced detection threshold. Likewise, electromagnetic inspection techniques benefit from the fact that noncubic systems exhibit electrically anisotropic properties, allowing for microstructural characterization, and suffer from the fact that the electrical scatter originating from varying local resistivity raises the noise floor, thereby reducing flaw detectability. The electrical anisotropy observed with eddy currents in noncubic metals is therefore analogous to the elastic anisotropy observed with ultrasonic techniques and has strong implications for the nondestructive evaluation of polycrystalline titanium alloys. In the case of titanium alloys of primarily hexagonal symmetry, arguments favor the use of both eddy current and ultrasonic techniques for materials characterization with both providing useful information about microstructure. Although the electrical anisotropy of noncubic crystals is a well known physical fact, to the best of our knowledge, the significant role played by the microscopic electrical anisotropy of individual grains in the macroscopic eddy current response of the polycrystalline material has only recently been pointed out and investigated in any depth [16].

ACKNOWLEDGMENTS

This effort was partially sponsored by the Defense Advanced Research Projects Agency (DARPA) Multidisciplinary University Research Initiative (MURI), under Air Force Office of Scientific Research grant number F49620-96-1-0442.

REFERENCES

1. J. H. Rose, in *Review of Progress in QNDE,* Vol. 11 (Plenum, New York, 1992) pp. 1677-1684.
2. F. J. Margetan, R. B. Thompson, and I. Yalda-Mooshabad, J. Nondestr. Eval. 13, 111 (1994).
3. K. Goebbels, in *Research Techniques in Nondestructive Testing* Vol. IV (Academic, New York, 1980) pp. 87-157.
4. A. Hecht, R. Thiel, E. Neumann, and E. Mundry, Mat. Eval. 39, 934 (1981).
5. H. Willems and K. Goebbels, Met. Sci. 15, 549 (1981).
6. C. B. Guo, P. Holler, and K. Goebbels, Acustica 59, 112 (1985).
7. W. A. Wooster, *A Textbook on Crystal Physics* (University Press, Cambridge, 1938).
8. J. F. Nye, *Physical Properties of Crystals, Their Representation by Tensors and Matrices* (Clarendon Press, Oxford, 1985).
9. G. T. Meaden, *Electrical Resistance of Metals* (Plenum, New York, 1965) p. 31.
10. J. E. Neighbor, J. Appl. Phys. 40, 3078 (1969).
11. V. M. Tatarnikov, Meas. Tech. 13, 877 (1970).
12. V. I. Gordienko and V. G. Rybachuk, Meas. Tech. 32, 371 (1989).
13. R. Pitchumani, P. K. Liaw, D. C. Yao, D. K. Hsue, and H. Jeong, J. Comp. Mat. 28, 1742 (1994).
14. R. Pitchumani, P. K. Liaw, D. C. Yao, D. K. Hsue, and H. Jeong, Acta. Metal. Mat. 43, 3045 (1995).
15. P. L. Rossitier, *The Electrical Resistivity of Metals and Alloys* (Cambridge University Press, Cambridge, 1987) pp. 185-195.
16. M. P. Blodgett, P. B. Nagy, Appl. Phys. Lett. 72, 1045 (1998).
17. H. L. Libby, *Introduction to Electromagnetic Nondestructive Test Methods* (Wiley-Interscience, New York, 1971).
18. A. Briggs, *An Introduction to Scanning Acoustic Microscopy* (Oxford University Press, Oxford, 1985). pp. 35-41.
19. D. Eylon, Met. Trans. A 10, 311 (1979).