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A unique nondestructive materials characterization facility has been established for non-contacting thermoelectric inspection of metals. The measurement system is based on a high-temperature SQUID magnetic scanner that is capable of detecting th weak magnetic field of thermoelectric currents developing around material imperfections when a conducting metal is subjected to external heating and cooling. Since the surrounding intact material serves as the reference electrode and there i no artificial interface between the host and the imperfect region to be detected, the inspection sensitivity is much higher than that of conventional thermoelectric systems. This new nondestructive inspection technique offers the following distinct advantages over conventional methods: (a) high sensitivity to subtle variations in material properties, (b) insensitivity to the size, shape, and other geometrical features of the specimen, (c) noncontacting nature with a substantial stand-off distance, and (d) the ability of probing deep into the material and penetrating through thick, multiple-layer structures. The potential applications of this method include detection metallic inclusions, segregations, inhomogeneities, and tight cracks as well as quantitative characterization of hardening, fatigue, texture, and residual stresses.

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FINAL PERFORMANCE REPORT

NONCONTACTING THERMOELECTRIC DETECTION OF MATERIAL IMPERFECTIONS IN METALS

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ABSTRACT

A unique nondestructive materials characterization facility has been established for noncontacting thermoelectric inspection of metals. The measurement system is based on a high-temperature SQUID magnetic scanner that is capable of detecting the weak magnetic field of thermoelectric currents developing around material imperfections when a conducting metal is subjected to external heating and cooling. Since the surrounding intact material serves as the reference electrode and there is no artificial interface between the host and the imperfect region to be detected, the inspection sensitivity is much higher than that of conventional thermoelectric systems. This new nondestructive inspection technique offers the following distinct advantages over conventional methods: (a) high sensitivity to subtle variations in material properties, (b) insensitivity to the size, shape, and other geometrical features of the specimen, (c) noncontacting nature with a substantial stand-off distance, and (d) the ability of probing deep into the material and penetrating through thick, multiple-layer structures. The potential applications of this method include detection metallic inclusions, segregations, inhomogeneities, and tight cracks as well as quantitative characterization of hardening, fatigue, texture, and residual stresses.

BACKGROUND

A variety of different physical principles have been exploited for nondestructive detection, localization, and characterization of material imperfections in metals. The most popular techniques rely on ultrasonic, eddy current, x-ray radiographic, magnetic, thermal, and microwave principles. A common feature of these conventional methods is that they are sensitive to both intrinsic material properties (e.g., electrical and thermal conductivity, permeability, elastic stiffness, density) and spurious geometrical features (e.g., size, shape, surface roughness). Unfortunately, these two classes of parameters are often very difficult to separate, which ultimately limits the detectable weakest material imperfection. In contrast, thermoelectric techniques are essentially free from geometrical limitations, i.e., they are solely sensitive to intrinsic material variations only regardless of the size, shape, and surface quality of the specimen to be tested. In spite of its obvious advantages over other methods in numerous applications requiring high sensitivity to subtle variations in material properties, conventional thermoelectric testing is rarely used in NDE because of the requirement that a metallic contact be established between the specimen and the reference electrode. This project was aimed at establishing an experimental facility to be used in the development of new noncontacting thermoelectric NDE techniques based on magnetic detection of local thermoelectric currents around imperfections when a temperature gradient is established in the specimen. This new facility will be used to study numerous applications of this novel method in nondestructive testing and materials characterization, that are of great interest to the Department of Defense including the Army, the Navy, and the Air Force.

METHODOLOGY

Essentially all existing thermoelectric NDE methods are based on the well-known Seebeck effect that is commonly used in thermocouples to measure temperature at the junction of two different conductors. Ideally, regardless of the temperature difference between the junctions of two metals, only thermocouples made of different materials, or more precisely, materials of different thermoelectric power, will generate thermoelectric signal. This unique feature makes the simple thermoelectric tester one of the most sensitive material discriminators used in nondestructive inspection. Unfortunately, the application of the conventional thermoelectric technique in nondestructive materials characterization is badly limited by the need for metallic contact between the reference electrodes and the part to be inspected. In addition, detection of small variations in the thermoelectric power of the material requires that a reference electrode of very similar material be used. Both limitations can be eliminated by the recently discovered noncontacting thermoelectric method based on magnetic sensing. A modest temperature gradient is induced in the specimen by directional heating and/or cooling. As a result, local thermoelectric currents are generated in the vicinity of material imperfections, which can be detected by scanning the specimen with a sensitive magnetometer. Since the surrounding intact material serves as the "reference" electrode and there is no artificial interface between the host and the imperfect region to be detected, the detection sensitivity to subtle variations in material properties could be very high assuming that the absolute sensitivity of the magnetometer is high enough to pick up the weak magnetic field of the thermoelectric currents in the specimen. As a result of recent technological advances in the development of high-sensitivity Superconductive QUantum Interference Device (SQUID) magnetometers, it has become feasible to adapt noncontacting magnetic thermoelectric inspection to many applications of great interest in NDE.

RESEARCH INSTRUMENTATION, EXPENDITURE

We received a $166,500-DURIP-award to establish a noncontacting thermoelectric NDE system based on a high-temperature SQUID magnetometer. This grant was originally approved for a 1-year period from 4/1/01 to 3/31/02. Upon receiving the award, UC immediately placed an order of $166,500 for the SQUID-based NDE scanner specified in the proposal and paid a 40% ($66,600) prepayment that was required by the manufacturer, FINO AG of Germany. Unfortunately, FINO AG could not deliver the product before the end of the 1-year project period, therefore we had to ask for a 1-year extension, which was granted by AFOSR on 3/29/02. Shortly before the expected delivery time, FINO AG did deliver the special computer-controlled nonmagnetic scanning table with shielding capabilities in the total value of $30,000, but also informed us that they would not be able to deliver the originally ordered system even by the end of this second period (3/31/03), therefore UC accepted the partial delivery, canceled the remainder of the order and requested a full refund for the outstanding $36,000. FINO AG could not immediately refund the outstanding part of our prepayment, therefore, after notifying AFOSR, we agreed to a refund offer from FINO AG to reimburse UC in 12 monthly installments.

At the same time, we requested from AFOSR an additional 1-year extension until 03/31/04 to finish the project, which was subsequently granted. We placed an order for a similar SQUID magnetometer with a US manufacturer, Tristan Technologies of California, who agreed to custom build a system for us for the $99,900 we had available at that point by using some of our existing equipment and the nonmagnetic turntable/scanner delivered by FINO AG. The SQUID magnetometer system was delivered by Tristan Technologies in November 2003.

The original FINO AG NDE system also included a special lock-in-amplifier component that allowed the SQUID magnetometer to be used as a very sensitive eddy current instrument. In order to provide this very useful feature with the Tristan system, we decided to purchase a precision Impedance Analyzer from Agilent Technologies for the $36,000 FINO AG agreed to repay. FINO AG started to reimburse UC in monthly installments in April, 2003 and finished by the end of 2003. Subsequently, we purchased the Impedance Analyzer and, after receiving the instrument from Agilent Technologies, we assembled and successfully tested the entire system and started our planned research activity.

ANTICIPATED BENEFITS

The recent adaptation of SQUID magnetometers for noncontacting sensing of thermoelectric currents will undoubtedly lead to a new surge of activity in thermoelectric NDE. The potential applications of this method cover a very wide range from detection of inclusions, inhomogeneities, and tight cracks to characterization of hardening, fatigue, texture, and residual stresses. The nondestructive methods to be developed by the help of the purchased research instrumentation have the following distinct advantages: (a) sensitivity to subtle variations in material properties such as increasing dislocation density before fatigue crack initiation, (b) insensitivity to the size, shape, and other geometrical features of the specimen, (c) noncontacting nature with a substantial stand-off distance that can be on the order of a couple of inches, and (d) probing very deep into the material and penetration through thick, multiple-layer structures. The primary applications of the proposed nondestructive materials characterization method are:

- Detection and quantitative characterization of fatigue damage, texture, and anisotropy.

- Assessment of shot-peening effects (surface hardening, texturing, residual stress) in titanium and aluminum alloys, nickel based superalloys, stainless steel, and other metals.
- Detection of partially closed fatigue cracks in aerospace materials.
- Detection of metallic inclusions and segregations in critical engine components (e.g., segregations in Inconel turbine discs, hard alpha inclusions in titanium alloys, etc.).
- Assessment of the integrity of welded, diffusion bonded, and brazed joints, rolling and forging inhomogeneities.

GRANTS RECEIVED/EXTENDED AS A RESULT OF THIS DURIP AWARD

Department of Energy, "Noncontacting Thermoelectric Detection of Material Imperfections in Metals," $497,246, September 2000-March 2005.

Department of the Air Force, "Nondestructive Residual Stress Management Methods for Engine Rotor Life Extension," $300,000, October 2003 – September 2005.

Department of the Air Force, "Nondestructive Evaluation of Residual Stress Relaxation in Surface-Treated Engine Alloys," $450,000, June 2003 – December 2008.

EDUCATIONAL BENEFITS

The new non-contacting thermoelectric NDE facility already serves a major role in our Aerospace Engineering and Engineering Mechanics Graduate Programs. Presently, two PhD students and two master students supported by Department of Energy and Department of Air Force grants are conducting their dissertation and thesis research using this instrumentation.

EQUIPMENT INVENTORY LOG

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CONTRACT/GRANT # : F49620-01-1-0293-DURIP

P.I. : Peter B. Nagy

AGENCY: Air Force Office of Scientific Research

QTY	DESCRIPTION	VENDOR	LOCATION	SERIAL/ MODEL #	DATE of PURCHASE	P.O. #	TAG #	COST	TYPE *
1	Nonmagnetic Scanner	FINO AG	475 ERC	730607/ HMT-1	04/11/2001	PC01M-08317	331615	$30,387	SPE
1	SQUID-based NDT system	Tristan Technologies	475 ERC	0108/ SMM-701U	02/12/2003	PC03M-05033	330452	$99,900	SPE
1	Precision Impedance Analyzer	Agilent Technologies	475 ERC	MY43200384/ 4294A	01/09/2004	PC04M-04057	344327	$36,213	SPE
	Total							166,500	

* TYPE: GFP = Government Furnished Property
SPE = Special Purpose Equipment
GPE = General Purpose Equipment