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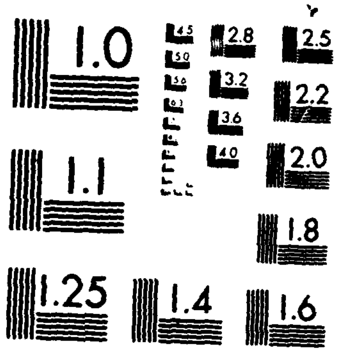

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A thermoelastic stress analysis system was purchased and put into operation, for the purpose of making dynamic measurements of stress fields in composite materials, and the changes in those fields caused by damage development under long-term loading conditions. The application was successful, but did require that a micromechanical thermoelastic theory be developed to assist in the interpretation of the patterns.

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THERMOELASTIC STRESS ANALYSIS SYSTEM

Final Report

AFOSR-85-0066

K. L. Reifsnider, Reynolds Metals Professor of

Engineering Science and Mechanics

Materials Response Group

Virginia Polytechnic Institute and State University

Blacksburg, Virginia 24061-4899

Abstract

Perhaps the single most important experimental requirement for the evaluation of the mechanical behavior of engineering materials is the determination of stress distributions under load. Experimental stress analysis is the basis for much of the engineering research and development presently conducted on solid materials. Many techniques have been developed for this purpose. However, some situations require very special procedures. If loads are applied synamically as in the cases of cyclic (fatigue) loading or vibration loading, measuring the full field stress distribution is greatly complicated. And secondly, when damage develops in materials, strong local gradients in stress result which are critically important in the determination of the remaining strength or life of the component.

Damage development in composite materials under cyclic and dynamic loading is an especially important example of this special need. These

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materials have become an important part of the economy of the United States and critical to its defense. Yet, an understanding of their durability and damage tolerance has not been established. Hence, we are unable to predict, from mechanistic models, the strength and life of these materials in service. A major obstacle to progress in this area is the lack of a technique to measure the complex stress distributions, especially during the fatigue or vibratory loading common to service conditions. In the last few years a new device has been developed that has demonstrated the capability to measure such stress fields using the principal of adiabatic temperature change pattern analysis. The present program provided support for the purchase of that device, which was used for stress analysis in a variety of DoD research programs at Virginia Tech, with special emphasis on the evaluation of stress fields in composite materials, especially during life-limiting damage development.

Research Program:

The instrumentation obtained in the present program was used to support several existing and proposed DoD research programs as described below. However, the principal thrust of the applications referred to in this report will be concentrated in two on-going DoD research efforts as described in this section. The thermoelastic instrumentation obtained with this grant uses infrared radiation to remotely measure minute local temperature changes produced by the thermoelastic effect in proportion to the distribution of stresses. The equipment has the following important features in the context of present applications.

a. The remote camera maps complete areas of actual or model structures.

b. Large or small areas can be studied.

c. The camera maps stresses in structures over a very wide range of dynamic loads, including fatigue conditions.

d. High sensitivity, in the range of a few hundred pounds per square inch of resolution, is possible.

e. Display and data analysis are immediately obtained.

f. The equipment is aided by microprocessor-controlled functions.

g. Calibration routines insure accurate quantitative analysis for a range of materials.

This device has made possible an entirely new comprehensive scheme for the interpretation of damage development in composite materials. For example, it is now possible to establish quantitatively the precise nature of stress redistributions caused by the development of complex patterns of matrix cracks, delaminations, and fiber fractures normally associated with damage development in these materials. Research conducted by the authors, and others, strongly suggests that these redistributions control the remaining strength and life of composite components. Hence, it should be possible to develop mechanistic models of the remaining strength and life under those conditions, a possibility of great potential value to the prediction of durability, damage tolerance, safety, and certified life of composite structures. Moreover, these thermoelastic techniques are of inestimable value to basic research efforts since they provide an absolute link between the micro-mechanics of damage development and the stress fields associated with those events. Indeed, it is hard to imagine a more powerful step that could be taken in the area of experimental damage analysis in composite materials.

The first major research program which the new instrumentation has supported is titled "Investigation of Damage Growth in Composite

Laminates: and is supported by the Air Force Office of Scientific Research under Grant No. AFOSR-85-0087. The principal investigators on that program are K. L. Reifsnider and W. W. Stinchcomb. The objectives of that program are to develop an understanding of damage initiation and growth in notched composite laminates and to develop a cumulative damage model which can be used to predict the strength, stiffness, and life for various load histories.

This research program involves an attempt to develop the first mechanistic model of cumulative damage development in notched composite laminates subjected to tension-tension, tension-compression, and compression-compression fatigue loading with constant and variable amplitudes. The mechanistic model that is under development is based on analytical representations of two basic physical phenomena--the degradation of physical elements in laminated composite materials, and the internal redistribution of stress caused by the failure of subcritical elements in those materials during cyclic loading. The experimental program associated with this effort has clearly demonstrated that the stress redistributions have a critical influence on the subsequent damage development and the remaining strength and life of the notched laminates. The determination of these stress redistributions is an extremely demanding task. Those redistributions are presently being slowly and meticulously determined using a moire diffraction technique which requires a highly sophisticated experimental laser-based optical system and the bonding of very high resolution diffraction gratings onto each of the specimens to be examined. Because of the delicate complexity of this technique, it cannot be used during cyclic loading. Photoelastic methods are also being used but dynamic application is not possible. Hence, the chronology, duration, and time-dependent details of these stress redistributions cannot be determined even with that technique.

The thermoelastic instrumentation purchased in the present program has made a critical contribution to this problem. The present investigators have shown that it is possible to record thermoelastic patterns which define the strain contours around the center hole in a notched composite laminate coupon specimen, and to follow these distributions as damage development causes stress redistribution in the laminate. Moreover, the initial thermoelastic patterns (before damage development has occurred) have been compared with both photoelastic back reflection patterns and analytical predictions of the strain profiles to verify the technique. To our knowledge, this is the first successful application of any method of direct measurement of strain distributions to a cyclic loading test. Moreover, it is the first application of thermoelastic strain measurement to anisotropic materials such as fibrous composite systems. Several reports and papers describing this work are under preparation.

During the course of this work, the authors made a very startling discovery. When the thermoelastic strain distributions around a notch such as a center hole in an anisotropic specimen, such as a laminated fibrous composite material coupon, were compared with the analytical computations of such patterns obtained from formulations of thermoelasticity which appear in the literature, it was found that the analytical predictions were not even approximately correct. These were not discrepancies or differences caused by magnitudes associated with approximations, etc., but rather they suggested a [illegible] misrepresentation of the physics by the analytical treatments. The present authors returned to first principles of physics and reformulated a micro-mechanical thermoelatic theory which was then applied to the anisotropic composite materials under test with dramatic success. This is, without question, the most salient success of this research program to date. It is a breakthrough in the sense that the classical thermoelastic theory for anisotropic materials does not describe the thermoelastic temperature distributions associated with the nonuniform strain in the neighborhood of notches in anisotropic materials such as laminated composites, but the micro-mechanical thermoelastic theory proposed by the authors matches every pattern recorded to date. This work is also being prepared for publication.

The title of the second program to be discussed is "Vibrothermography: Development of a New Nondestructive Testing Technique for Composite Materials." This program is funded by the Army Research Office under Grant DAAG-29-79-G-0037. The principal thrust of that research program is to develop the nondestructive test technique called vibrothermography for the purpose of the detection, interpretation, and analysis of damage development in composite materials during quasistatic and cyclic loading for the purpose of determining and predicting the strength, stiffness, and life of those materials in engineering components. The concept and technique of vibrothermography was originated by investigators in the Materials Response Laboratory, authors of this report, at Virginia Tech [1]. In simple and general terms, the technique incorporates mechanical excitations of various frequencies and amplitudes to induce dissipative heat emission by the specimens under examination. This heat emission forms temperature patterns which re related to the internal distributions of stress and the development of damage during the loading processes. These patterns can be directly related to the collective influence of the complex distributed damage events that control the stiffness, strength, and life of composite materials. This new technique has attracted a great deal of attention in the last few years and has been adopted for use in research and development by a number of laboratories including several NASA installations and Army labs. Under a DoD contract (#DAAG 29-76-D-0100) the authors recently wrote a state-of-the-art review of thermography as applied to composite materials in association with the Manufacturing Methods and Technology (MANTECH) Program. (See Ref. [2].) The present authors have written over a dozen other articles on the technique, as well as a recent chapter in a book (Ref. [3]) and are presently negotiating a contract to write a monograph on the subject.

The instrumentation purchased through the present program is being used to provide the critical link in the research program described above. The vibrothermography technique that we have developed is capable of measuring only dissipated energy, i.e., the energy that is released in the form of heat as a result of damage formation processes in the interior of the composite (or other) materials being studied. While information regarding the energy released by these processes is critical to the detection and interpretation of damage, it is only half of the story. It is equally critical to know the stress distributions and redistributions associated with those damage events. That information is presently missing in the vibrothermography technique that is used, and represents a major obstacle to continued development of this important method.

As this effort progresses, the thermoelastic instrumentation will make possible for the first time a complete analysis of the changes in energy associated with damage development in composite materials subjected to load histories associated with in-service environments. Energy released by damage formation can be detected by vibrothermography while energy stored by elastic deformations can be detected by thermoelastic temperature changes.

Other Anticipated Applications:

The instrumentation purchased in this program is a unique computer-controlled instrument for non-contact measurement of dynamic stresses in components and structures. The need for such a capability is pervasive and important in nearly all research conducted on the mechanical response of solid materials. The instrument purchased from the present grant will directly impact and support seven on-going Department of Defense research contracts listed below, having a total level of support of about $1,450,280.

"A New Nonlinear Model for the Loading and Unloading Behavior of Carbon-Carbon Composite Materials," NSWC/Dahlgren, $81,953.

"Investigation of Micro-damage in Composite Materials," ARO, $36,434.

"Vibrothermography: Investigation, Development and Application of a New Nondestructive Evaluation Technique," ARO (DAAG-29-79-G-0037) $162,792.

"Center for Adhesion Science," ONR (N00014-82-K-0185), $37,181.

"An Interdisciplinary Approach to the Prediction and Modeling of Structural Adhesive Bonding,"

"Application of Lightweight Composite Materials to Naval Weapons Systems," Navy/NRCC, Philadelphia (N00140-83-C-6684), $99,921.

"High Performance Elstomers and Other Multi-Phase Organic Composites," ARO (DAAG-2980-K-0093), $800,000.

"Fundamental Studies of the Effects of Thin Polymeric Surface Films in Reducing Fretting Corrosion and Wear," ARO (DAAG-29-83-K-0157), $15,000.

It is not prudent or possible to describe the exact relationship of the proposed instrumentation to the activities of each of the research programs listed above. Instead, three of the programs will be specifically mentioned below to provide a cross-section of that interaction.

The first example program is supported by the Office of Naval Research, a grant titled "An Interdisciplinary Approach to the Prediction and Modeling of Structural Adhesive Bonding." The contract number for that grant is N00014-82-K-0185; the program is funded at a level of about $200,000 per year. The object of that program is to bring about the interaction of students and faculty from the disciplines of chemistry, materials, and mechanics to utilize a combination of principles from those disciplines so as to achieve the control, analysis, and property prediction of adhesive bonds in engineering structures. This program is the centerpiece of the newly established Center for Adhesion Science which was initiated at Virginia Tech in 1982 with enabling funds from the Office of Naval Research. The purpose of that Center is to create a climate for the interaction of students and faculty, to provide laboratory assistance for such studies, and to produce graduates who are knowledgeable in the science and engineering of adhesion and adhesive bonding.

The two major concerns of this research program are the integrity of the adhesive bond and the stress fields and deformation fields that develop in those bonds. The instrumentation requested in this proposal will directly impact the study of both of those subjects. At present, there is no suitable method or technique available for the study of stress distributions and adhesive bonds, especially under dynamic loading. While some efforts have been made to use embedded strain gages and a variety of optical techniques to obtain limited information about those stress fields, there is a critical need for a technique which has more general capabilities for the measurement of these stress distributions and their changes during the loading of adhesive bonds. All available information suggests that the requested instrumentation could make an important contribution to this need.

The second need mentioned above is for a technique to assess the quality of integrity of an adhesive bond. One of the factors known to influence this integrity is the presence of flaws or defects such as porosity and poorly bonded regions. These defects are known to influence the micro-stress distributions in a complex way that has not been determined. It is proposed to attempt to apply the requested instrumentation to the study of such micro-stress variations. In general, stress distributions in joints are complex and nonuniform. The instrument that is requested in this proposal is designed specifically and exclusively for the purpose of determining the nature of such nonuniform stress fields.

The second example program to be mentioned explicitly is funded by the Army Research Office under Grant #DAAG-29-80-K-0093, and is titled "High Performance Elastomers and Other Multi-Phase Organic Composites." The total level of support for that research contract is about $800,000. The general objective of that program is to develop, characterize, and apply multi-phase organic composites which are said to be "self-reinforcing."

Two general classes of materials are addressed by this example program: elastomeric block co-polymers, especially co-polyesters, and thermotropic liquid crustal polyesters. A number of these systems can be formulated and fabricated in such a way that the micro-phases separate during solidification to form "reinforcing" phases at the molecular level. In a sense, they are molecular composites. As such, they are anisotropic and inhomogeneous at the micro level and have bery complex stress distributions when loaded mechanically. From an engineering standpoint, one of the more important characteristics of these materials is that the reinforcing phases can be made to follow the directions of flow when these materials are fabricated. For example, if the material is cast around a bolt to form a bolt hole, the molecular reinforcement arranges itself to coincide with the flow pattern around the bolt. This flow-related reinformcement greatly influences the subsequent stress distributions in the vicinity of stress concentrations such as notches, bolt holes, and other cutouts. Since these materials are almost universally opaque, there is presently no optical technique that can be applied directly to the determination of the stress distributions under such circumstances. Hence, it is very difficult to study this self-orienting effect and the positive or negative aspects of the stress distributions that occur because of those phenomena. It is anticipated that the proposed instrumentation will enable investigators to study the complex stress distributions associated with self-reinforcing (molecular) composites in general and to study the complex stress fields associated with flow patterns and self-orientation of the molecular reinforcements in particular.

The third example program is titled "Fundamental Studies of the Effects of Thin Polymeric Surface Films in Reducing Fretting Corrosion and Wear." This program is funded by the Army Research Office under Contract #DAAG-29_83-K-0157 at a level of about $15,700. The objective of this example program is to understand the nature of the effects caused by the application of thin films of polymeric materials to metallic surfaces which undergo small amplitude relative displacements due to vibration loading.

While the engineering aspects of friction and wear have been studied for some time, the fundamental principles associated with such behavior are incompletely understood. One of the obstacles to the development of such understanding is the extreme difficultyinvolved in the development of experimental techniques which can be used to determine the physical behavior associated with friction processes. The objective of this example program is to alter just such processes, and to develop an understanding of how that alteration influences the resultant behavior. However, it is extremely difficult to obtain any information regarding the deformation processes that occur in the polymeric film that is applied between the two metallic surfaces. One experimental scheme that is presently being attempted is to replace one of the metal surfaces with a transparent material so that the interaction between the polymeric film and the fretting surfaces can be observed optically. It would be of great value if, under those circumstances, the proposed instrumentation could be used to also determine the nature of the stress fields that develop in the polymeric film and the surrounding surfaces during the wear process. Indeed, the successful observation and quantitative determination of such stress fields would be a breakthrough in this field. Hence, the thermoelastic stress analysis device purchased under this contract proposal will be used to attempt to determine the nonuniform stress fields associated with fretting and friction and wear processes, especially for situations in which thin polymeric surface films are introduced to reduce the degradation associated with those processes.

Application of the instrumentation to other research efforts that are supported and of interest to the Department of Defense could be discussed. The number of such topics that are related to stress analysis is large--topics associated with such general fields as the validation of analytical and numerical stress analysis, the detection and investigation of stress anomalies associated with defects and stress concentrations, study of creep and fatigue behavior, nondestructive testing and evaluation, and general materials testing. While technical limitations will certainly prevent the instrumentation from being successful in its application to all of these topics, it would appear that this instrumentation which operates on the basis of simple physical principles holds the promise of opening up entirely new areas of experimental investigation that can reasonably be expected to have a major impact on the objectives of a variety of Department of Defense research efforts.

Closure:

The purchase of the Thermoelastic Stress Analysis System with the DoD-URIP grant and the associated research program has satisfied every goal and objective stated in the original proposal. Indeed, it has far surpassed the original expectations in the sense that a breakthrough in the understanding of the thermoelastic effect in anisotropic materials has been achieved through the interpretation of data developed with this device in support of a new micro-mechanical formulation of anisotropic thermoelastic theory. Not only has the device made significant contributions to the understanding of damage development and growth in composite materials, it has opened up a new investigative avenue to researchers and engineers who are concerned with the degradation of materials over time and the associated modeling of remaining strength and life, matters which are of great consequence to the safety and reliability of engineering components and structures. The useful life of this equipment has not been determined since it has only been in service for about five years. However, the present authors hve had extensive experience with thermographic equipment which is quite similar in basic construction to this device, which indicates that, with minor repairs, the instrument can be maintained in essentially perfect working order for periods of 15 to 20 years.

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