RESIDUAL STRESS EFFECTS IN FATIGUE

A symposium
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Committee E-9 on Fatigue
Phoenix, Ariz., 11 May 1981

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symposium chairmen

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Foreword

The Symposium on Residual Stress Effects in Fatigue was held in Phoenix, Arizona, on 11 May 1981. ASTM Committee E-9 on Fatigue was sponsor. J. F. Throop and H. S. Reemsnyder served as symposium chairmen.

Related ASTM Publications

Low-Cycle Fatigue and Life Prediction, STP 770 (1982), 04-770000-30

Design of Fatigue and Fracture Resistant Structures, STP 761 (1982), 04-761000-30

Methods and Models for Predicting Fatigue Crack Growth under Random Loading, STP 748 (1981), 04-748000-30

Statistical Analysis of Fatigue Data, STP 744 (1981), 04-744000-30

Fatigue Crack Growth Measurement and Data Analysis, STP 738 (1981), 04-738000-30

Tables for Estimating Median Fatigue Limits, STP 731 (1981), 04-731000-30

Fatigue of Fibrous Composite Materials, STP 723 (1981), 04-723000-33

Effect of Load Variables on Fatigue Crack Initiation and Propagation, STP 714 (1980), 04-714000-30

Part-Through Crack Fatigue Life Prediction, STP 687 (1979), 04-687000-30

A Note of Appreciation to Reviewers

This publication is made possible by the authors and, also, the unheralded efforts of the reviewers. This body of technical experts whose dedication, sacrifice of time and effort, and collective wisdom in reviewing the papers must be acknowledged. The quality level of ASTM publications is a direct function of their respected opinions. On behalf of ASTM we acknowledge with appreciation their contribution.

ASTM Committee on Publications

Editorial Staff

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Introduction

The Symposium on Residual Stress Effects in Fatigue was organized to bring together new observations and analyses developed mainly from the application of fracture mechanics and local strain concepts to the estimation of fatigue life when residual stresses are present in a component. The use of superposition of stress intensity factor relationships, including expressions that consider residual stresses, has become widely accepted in recent years. Such superposition allows the analytical estimation of fatigue life rate to include residual stress effects on fatigue crack propagation.

Investigators active in the field of fatigue of materials are well aware, however, that if reliable fatigue life estimates are to be made, it is necessary to characterize the residual stress fields in test specimens and engineering components. Such characterization must include both analytical and experimental determinations of the residual stress distributions and their possible changes during the life of the component. Indeed, ASTM Subcommittee E09.02 on Residual Stress Effects in Fatigue and this symposium are the outgrowth of a 1976 task group study on organizing an activity for investigating the effects of residual stress in fatigue crack initiation, growth, performance, and life; seeking ways to measure those effects; and studying means of alleviating the adverse effects and exploiting the beneficial effects on fatigue behavior.

New techniques for analytical solutions of residual stresses, employing analogous thermal stress distributions, are becoming available. Also, experimental methods and instruments for residual stress measurement by X-ray diffraction, hole-drilling, and other techniques are being improved and becoming more widely available. Moreover, in the years since 1976 a rapid increase in awareness of the importance of residual stresses in material behavior has developed worldwide.

Because of these developments, May 1981 seemed a propitious time for ASTM Committee E-9 on Fatigue to sponsor a symposium exploring the present state of the art on residual stress effects on the fatigue behavior of materials. Many of the papers indicate that the newest developments of knowledge in the field are strongly influenced by the concepts of local strain analysis and linear elastic fracture mechanics. Some of the papers also treat recently developed techniques for observing the effects of residual stresses experimentally, such as ultrasonic methods, fretting fatigue experiments, and *in situ* observations of surface microcrack opening displacements in a scanning electron microscope. Along with a summary of methods for residual stress measurement and a presentation of standards for residual stress measurement, a variety of subjects was covered, including stress intensity factors, notches, weld fatigue, crack propagation in welds, welded joints, welded attachments, railroad rails, case-hardened steels, and aircraft landing-gear maintenance. These contributions show how the presence of residual stresses, either intentionally or unintentionally introduced, may affect the fatigue behavior of various specimens and structural components. They also indicate how one may take these effects into account quantitatively by measurement or analysis.

It is well known that large changes in fatigue life may result from varying the residual stress magnitude or distribution, especially if it is a compressive residual stress as in a shot-peened surface. It follows logically that considerable scatter in fatigue life at a given load level will result if the residual stress state in the component is not controlled within close limits. It has only recently been recognized that even in laboratory testing of specimens the fatigue performance may be incorrectly evaluated if the residual stress state of the specimens is not considered. Furthermore, while it has long been recognized that residual stresses may change during continuous load cycling (sometimes called "fading") it is only recently that analytical approaches—for example, local strain—have been developed for evaluating their changing magnitude during cycling. These aspects of fatigue behavior are discussed in several of the symposium papers.

This volume, then, should help the student, researcher, and engineer to become aware of the possible magnitude, nature, and consequences of residual stress effects in fatigue of materials. It also offers examples of analysis, instrumentation, and procedures currently used in evaluating these effects. We hope that future research and developments in the field will bring about improvements in, and new and better methods of, inspection, analysis, and measurement of the residual stress effects throughout the useful life of a component or structure.

We express our thanks and appreciation to the authors for their symposium presentations and papers. Special thanks are also due Darrell F. Socie and the members of the Joint ASTM E-9/E-24 Task Group on Fatigue of Short Cracks for their part in the consideration of that aspect of the subject. In addition, we thank the many reviewers for their time, effort, and helpful criticisms of the manuscripts.

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Nondestructive and Semidestructive Methods for Residual Stress Measurement

REFERENCE: Ruud, C. O., **"Nondestructive and Semidestructive Methods for Residual Stress Measurement,"** *Residual Stress Effects in Fatigue, ASTM STP 776,* American Society for Testing and Materials, 1982, pp. 3-5.

ABSTRACT: The effect of residual stresses on the fatigue life in metallic components has long been recognized. However, the most commonly employed methods for its measurement are destructive or at least partially so. This has led to an active interest in nondestructive methods for residual stress measurement. A review and evaluation has recently been published that describes the essence of the principles of nearly all the applied and proposed methods for nondestructive and semidestructive residual stress measurement. This review is summarized herein.

KEY WORDS: residual stresses, stress measurement, nondestructive stress measurement, semidestructive stress measurement, hole drilling stress measurement, X-ray diffraction stress measurement, ultrasonic stress measurement, Barkhausen noise analysis

Residual stresses have been given many labels, including *internal, bulk, self, welding, forming, fabrication*, and *in situ stresses*. However, these other names are not as specific or else they are less comprehensive than the preferred term, *residual stresses*. Residual stresses are produced in metals by most processes used to form and fabricate them into engineering components. This includes welding, forging, heat treating, rolling, grinding, machining, etc. These processes cause residual stresses by inducing plastic deformation of the metal through severe temperature gradients or mechanical forces. A less common source of residual stress which is not the direct result of plastic deformation is localized permanent elastic expansion or contraction of the metallic lattice in processes such as nitriding, carburizing, or heat treatment which induces phase transformation.

Background

For many reasons, residual stresses are receiving increased attention by the engineering community. These reasons are primarily concerned with pressures to reduce the cost of materials used in structures, extending the useful lifetime of

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existing structures, and the demand for greater reliability of structural components. This has led to much activity in the study of residual stress measurement methodologies, especially those which may be applied to nondestructive inspection. Unfortunately, those methods of residual stress measurement with which the engineering community is most familiar are completely destructive. This has precipitated greater activity in the research and development of nondestructive, or at least semidestructive, methods of residual stress measurement.

An in-depth review and evaluation has recently been completed on nondestructive methods of residual stress measurement.[2] This EPRI Report is summarized herein. It focuses upon nine generic types of stress measurement-related phenomena:

1. Ultrasonic (Acoustics)
2. Electromagnetic (including Barkhausen)
3. Neutron Diffraction
4. X-Ray Diffraction
5. Positron Annihilation
6. Nuclear Hyperfine (including Mossbauer)
7. Chemical Etchant
8. Indentation
9. Hole Drilling

A condensation of this full report was recently published,[3] which focused upon the four most useful and/or most studied nondestructive and semidestructive methods. These were ultrasonic, Barkhausen, X-ray diffraction (XRD), and hole drilling.

Conclusions

The EPRI Report concluded that the most reliable methods, besides the completely destructive mechanical methods, for the measurement of residual stresses are hole drilling and X-ray diffraction. The semidestructive method of hole drilling is capable of measuring stresses to a depth of a few millimetres into the specimen, and the instrumentation is portable and inexpensive. However, the application of this method could well weaken the component to the extent that it would no longer be functional. Furthermore, there are many other limitations of the hole-drilling techniques; these are described in the EPRI Report.

The X-ray diffraction method is recognized as the only truly nondestructive residual stress measurement technique that is reliable. Its most severe limitations are that it can be applied nondestructively only on the surface, instrumentation is expensive, and procedures for the newly available portable instrumentation are not yet ready for general application. Other less serious limitations are detailed in the EPRI Report.

[2] Ruud, C. O., "A Review and Evaluation of Nondestructive Methods For Residual Stress Measurement," EPRI Report NP-1971, Project 1395-5, Electric Power Research Institute, Palo Alto, Calif., Sept. 1981.

[3] Ruud, C. O., *Journal of Metals*, Vol. 33, No. 7, July 1981, pp. 35-40.

The ultrasound methods hold the greatest promise for wide practical application, especially for three-dimensional stress fields; however, their general implementation is by no means likely to evolve in the near future. Most of the other methods that have been proposed, including Barkhausen Noise Analysis, are either of such limited use or in such an elementary state of development that their practical implementation is likely to be further away than that of ultrasound.

The prognosis offered is that the semidestructive method of hole drilling will continue to find limited application, especially where its use can be tolerated and where investment in XRD instrumentation is fiscally prohibitive. However, the technology for portable XRD equipment capable of rapid, accurate residual stress measurement is advancing, and more versatile devices will become available over the next few years. This will set the stage for much more widespread field and shop use of XRD, even for dynamic and high-temperature applications. The ultrasonic techniques will enjoy the most intense research investment and will continue to offer the promise of three-dimensional nondestructive residual stress measurement; however, general practical implementation is years away, even though instrumentation for ultrasound is by nature easier to make portable than the XRD counterpart. The major impediments to ultrasound residual stress technology will remain the need for better understanding of the effect of microstructural characteristics of metals on the ultrasonic wave, development of vectorial algorithms for acoustic propagation and velociometric effects, higher-quality more-versatile transducers, and better transducer/metal coupling technology. The Barkhausen technique of residual stress measurement suffers from as many inherent unknowns and limitations as does ultrasound without offering as much promise for general practical applicability. Any advancements in the magnetic or other methods are likely to come by chance from research applied to basic knowledge or goals other than NDE for residual stress measurement.

Leonard Mordfin[1]

Standards for Residual Stress Measurement

REFERENCE: Mordfin, Leonard, **"Standards for Residual Stress Measurement,"** *Residual Stress Effects in Fatigue, ASTM STP 776,* American Society for Testing and Materials, 1982, pp. 6-12.

ABSTRACT: It has been long appreciated that residual stresses can exert significant influences on fatigue and fracture behavior, but only recently have analytical models been developed which enable the influences to be quantified. These new capabilities have fostered increased demands for residual stress measurements and these, in turn, have revealed that the reliability and the reproducibility of such measurements are often less than adequate. The need for standards for residual stress measurements is now recognized as being urgent. Few standards presently exist, and they do not provide the required levels of measurement reproducibility.

Several organizations are attempting to respond to this critical need. This paper is a status report on the growing national effort to develop voluntary consensus standards to enhance the reproducibility of residual stress measurements. This effort has achieved noteworthy progress in only a few years, but it has also become evident that further progress will be increasingly more difficult because our understanding of some residual stress phenomena is limited. There is need for a national *research* effort to parallel and to support the standardization effort.

KEY WORDS: fatigue, hole drilling, nondestructive evaluation, photoelasticity, research needs, residual stress, standards, stress measurement, terminology, ultrasonics, X-ray diffraction

The phenomenon of residual stresses has been recognized for a long time and some methods for measuring residual stresses have been known for almost as long. Until recently, however, there were virtually no standards for residual stress measurement, because there was no general requirement to measure residual stresses accurately. Simply knowing whether the stresses in a certain region of a given part were tensile or compressive, or high or low, was usually sufficient to make a qualitative determination of whether the fabrication process for the part was acceptable or whether it had to be modified. In other words, there was no particular benefit to be derived from knowing whether the residual stress level was, say, 60 percent or 75 percent of the material yield strength.

This relatively comfortable situation (ignorance is bliss?) no longer prevails in many engineering applications. The development of analytical fracture mechanics and methods for predicting fatigue crack growth rates has made it possible to make quantitative estimates of the performance and durability of load-bearing

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elements. With these new capabilities, critical parts can be designed and fabricated with greater reliability than ever before, provided that the stresses acting on the parts are well characterized. A design engineer can often estimate applied stresses rather accurately if he knows the service loads and the conditions under which a part is expected to operate. However, the residual stresses, which can be just as detrimental as applied stresses, can only be characterized on the basis of measurements. The reliable measurement of residual stress has therefore become an elusive goal in many organizations that are concerned with the fatigue and fracture of critical parts.

There are numerous situations in which the design engineer would like to be able to specify maximum and minimum residual stress levels. One can also visualize inspection procedures that will monitor the residual stress distributions of critical parts in service in order to assure safety and durability. In scenarios such as these, which are not at all unrealistic for the latter part of this decade, it is imperative that residual stress measuring techniques be quantitative and reproducible; this requires measurement standards. The realization of this need prompted the creation of several groups, over the past few years, which are vigorously pursuing the development of standards for residual stress measurement.

Some Recent History

In 1976 ASTM Committee E-9 on Fatigue established the Task Group on Residual Stress Effects in Fatigue under the chairmanship of Joseph Throop of Watervliet Arsenal. Throop appreciated the importance of the measurement problem and formed a section, within the task group, to concern itself with the measurement and characterization of residual stress fields; this despite the fact that the topic was not in the mainstream of the task group's interest. In 1980 the task group became Subcommittee E9.02 on Residual Stress Effects in Fatigue.

The Society for Experimental Stress Analysis (SESA), under the instigation of Paul Prevey of Lambda Research, created the Technical Committee on Residual Stress Measurement in 1978. The principal functions of the committee are to promote research and to disseminate information on residual stress measurement. With Prevey as chairman, however, the committee also pursued round-robin testing programs aimed at providing some of the data needed to establish meaningful standards for residual stress measurements. Michael Flaman of Ontario Hydro is the present chairman of the committee, with Richard Chrenko of General Electric serving as chairman of the committee's executive board.

Also in 1978, Alfred Fox of Bell Laboratories, then chairman of ASTM Committee E-28 on Mechanical Testing, recognized the need for residual stress measurement standards and asked the author to organize the Task Group on Measurement Methods for Residual Stress. A year later the task group became Subcommittee E28.13 on Residual Stress Measurement, its principal mission being the development of consensus standards for residual stress measurement. The subcommittee is presently comprised of five sections: 01 on Nomenclature, 02 on Hole-Drilling Methods, 03 on X-Ray Diffraction Methods, 04 on Dissection and Layer-Removal Methods, and 05 on Ultrasonic Methods. With the establishment of E28.13, Throop was able to de-emphasize E9.02's direct concern with measurement methods.

In 1980 ASTM Committee D-20 on Plastics initiated Section D20.10.23 on Residual Strain Measurement, with Alex Redner of Vishay Intertechnology as its chairman. The chief interest of the section is the measurement of strains in plastics by photoelastic techniques.

It is a source of great satisfaction that the cooperation between all these groups has been excellent, since this is unquestionably enhancing the standards-development process.

Present Activities

There are, today, no national standards in the United States that address generic methods for measuring residual stresses. There are some company standards and some product standards, but the engineer or the technician who needs a standardized methodology or a traceable calibration procedure to guide him and to help him to make reliable and reproducible measurements of residual stress is generally at a loss in this respect. Fortunately, however, rapid progress is being made on this front, and it is reasonable to expect that consensus standards will begin to become available later in 1981.

X-Ray Diffraction

The well-known manual on "Residual Stress Measurement by X-Ray Diffraction" was published by the Society of Automotive Engineers (SAE) in 1960; an updated edition was issued in 1971 [*1*].[2] This is unquestionably one of the finest technical documents assembled by a committee and, until recently, it represented the single most complete and reliable American document on the subject. Few practitioners of the art can be found who are not intimately familiar with its hundred-plus pages. Recently, however, some detailed review articles have appeared (for example, Ref 2) which provide more up-to-date treatments of certain aspects of the subject than are available in the ten-year-old manual.

SAE J784a, as the manual is commonly known, has frequently been cited as a standard, but it is not nor was it intended as such. Although it describes various testing techniques clearly and thoroughly, it prescribes none. Two laboratories could well conduct residual stress measurements "in accordance with SAE J784a" and yet do virtually nothing in common. The three-point parabola procedure for determining peak diffraction angles, for example, has occasionally been termed "the SAE method" but, in fact, SAE J784a describes other procedures as well.

The committee that prepared the manual has undergone several changes over the past few years under SAE reorganizations and is presently known as the X-Ray Task Group of the Materials Properties and Processing Effects Division, an arm of the SAE Fatigue Design and Evaluation Committee. John Larson of

[2] The italic numbers in brackets refer to the list of references appended to this paper.

Ingersoll-Rand, an associate editor of SAE J784a, is the chairman of the group. In recent years the group directed its principal attention to the measurement of retained austenite by X-ray methods and has, apparently, ceased to address the residual stress problem. This is unfortunate, because the group has the competence to successfully formulate some of the needed test method standards for residual stress measurements. That such standards are feasible has already been demonstrated abroad.[3]

ASTM Subcommittee E28.13 has elected to pursue a different, although equally important, standards aspect of the X-ray diffraction method, namely the alignment and the calibration of the diffraction apparatus. Section 03 of the subcommittee, under Prevey's leadership, has prepared a "Standard Method for Verifying the Alignment of Instrumentation for Residual Stress Measurement by X-Ray Diffraction," which is expected to be balloted at the subcommittee level late in 1981. The method relies on the use of a stress-free metal powder as a reference specimen. The data that verify the stress-free nature were obtained in an SESA round-robin testing program initiated by Prevey, assisted by John Cammett of Metcut Research, for the SESA committee.

A second project in Section 03 of Subcommittee E28.13 is concerned with the calibration of the diffraction instrument. Based on earlier work by Prevey [*3*], a standard procedure will be formulated for evaluating the effective elastic constants which are needed to convert lattice strain measurements to stress values.

Hole Drilling

The most rapid progress in Subcommittee E28.13, thus far, has been achieved by Section 02 under Redner's direction. With considerable assistance from M. R. Baren of the Budd Company, Redner prepared a "Standard Method for Determining Residual Stresses by the Hole-Drilling Strain-Gage Method". The method has been approved by the Society and will be published in the *1982 ASTM Book of Standards*. The section is now making plans for a round-robin testing program, perhaps in collaboration with the SESA committee, to support the development of a more quantitative estimate of the precision of the method.

Photoelasticity

The photoelastic approach to evaluating the residual stresses in optically birefringent materials is also benefiting from Redner's leadership. Although some standards for this method have been available for some time,[4] they do not provide the quantitative precision needed for fracture mechanics analyses and, furthermore, they are applicable only to glass. In response to these limitations, ASTM Section D20.10.23 has developed a "Standard Method for Photoelastic Mea-

[3] "Standard Method for X-Ray Stress Measurement," Committee on Mechanical Behaviour of Materials, The Society of Materials Science, Japan, 20 April 1973.

[4] ASTM Tests for Polariscopic Examination of Glass Containers (C 148) and ASTM Test for Analyzing Stress in Glass (F 218).

surements of Strains in Transparent or Translucent Plastic Materials," which is expected to be approved by the Society in 1982.

Terminology

The difficulties in achieving consensus definitions of terms related to residual stress can only be appreciated by those who have tried it. There are very good reasons why standard definitions do not already exist for such "obvious" terms as *residual stress* and *residual strain*. After several years of persistent effort Section 01 of Subcommittee E28.13 has finally come up with definitions for these and other terms and a subcommittee letter ballot is expected late in 1981. The eventual intent—at this stage, at least—is to incorporate these definitions into ASTM Definitions of Terms Relating to Methods of Mechanical Testing (E 6).

Future Directions

The consensus standards for residual stress measurement that are now under development are based upon reasonably well-established practices. Well-established practices are not always available, however, to support every standard that merits development. In some cases there is inadequate understanding of all the physical phenomena involved and even some uncertainty regarding the most promising standardization approaches which should be pursued. This is a problem that has existed, for example, in connection with ultrasonic and magnetic methods for measuring residual stress.

Thomas Proctor of NBS, chairman of Section 05 in Subcommittee E28.13, addressed this problem by organizing the ASTM Symposium on Ultrasonic Measurements of Stress in collaboration with Joseph Heyman of NASA/Langley. The symposium, which was held in April 1981, brought together a number of experts on the subject and did, indeed, provide some of the guidance and direction that were sought. It became clear, as paper after paper was presented, that the principal barrier inhibiting further development and widespread application of ultrasonic techniques for residual stress measurement is inadequate understanding of the effects of microstructural features on ultrasonic wave propagation. That points up a need for an intensive research effort which an ASTM committee can certainly encourage but cannot hope to conduct. In fact, the effects of microstructure on ultrasonic wave propagation represents only one of several unsolved problems relating to residual stress measurement. NBS, through its Office of Nondestructive Evaluation, has proposed a framework for a comprehensive research program on this subject that is responsive to national priorities for enhanced productivity and product quality [*4*].

A panel discussion in the Symposium on Ultrasonic Measurements of Stress revealed that, in spite of the gaps in our understanding, there are at least three standardization activities, pertaining to the ultrasonic measurement of residual stress, which Subcommittee E28.13 can and should pursue: (*1*) the formulation