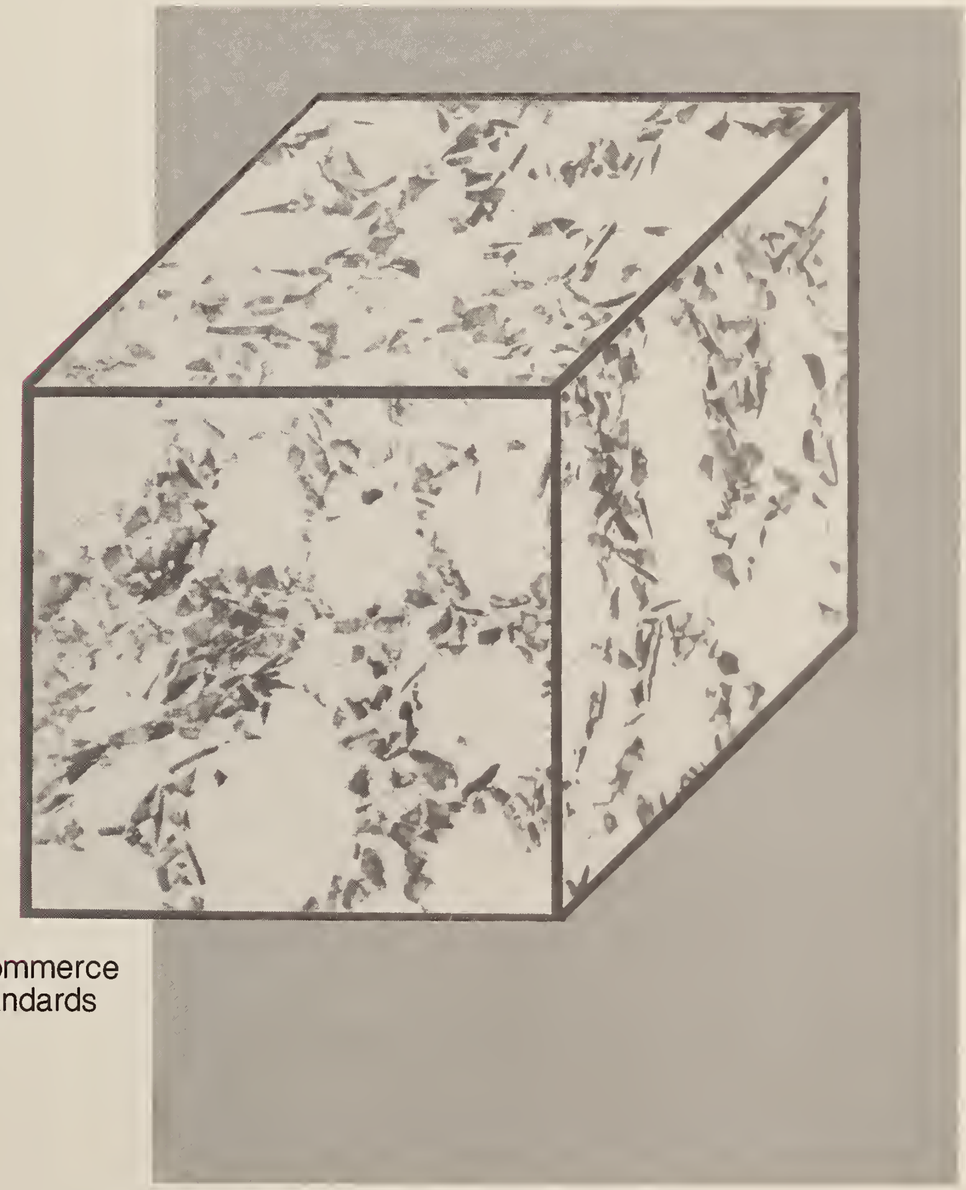
Institute for Materials Science and Engineering

FRACTURE AND DEFORMATION



NBSIR 85-3189
U.S. Department of Commerce
National Bureau of Standards

Technical Activities 1985

Photomicrograph of SiC/Al-alloy composite formed from powders of SiC and Al alloy. The SiC particles are represented as prolate ellipsoids with an aspect ratio of 3.0. The large Al "islands" are represented as oblate spheroids (aligned in the rolling plane) with an aspect ratio of 0.33. The randomly oriented SiC particles exist in a "sea" where the SiC volume fraction is approximately double that of the macroscopic average volume fraction. Taken from the paper "Elastic Constants of an Anisotropic, Nonhomogeneous Particle-Reinforced Composite" by H. M. Ledbetter, S. K. Datta and R. D. Kriz.

Photomicrography by Leonard C. Smith

Institute for Materials Science and Engineering

FRACTURE AND DEFORMATION

R. P. Reed, Chief
H. I. McHenry, Deputy

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ABSTRACT

This report summarizes the technical program of the Fracture and Deformation Division of the Institute for Materials Science and Engineering, National Bureau of Standards for the fiscal year 1985. The division's two major program areas are: elastic-plastic fracture mechanics and fracture mechanisms and analysis. Elastic-plastic fracture mechanics includes contributions from stress analysis, material properties, nondestructive inspection, and welding. Division efforts in fracture physics, time-, structure-, and temperature-dependent properties, composite mechanics, and material performance comprise the second area, fracture mechanisms and analysis. Significant technical programs relating to each of these are presented. Major accomplishments are highlighted, including very successful dynamic crack arrest measurements using 10-m-long specimens, development of the dynamic theory of crack tip-dislocation interactions, and continued development and application of finite-element analysis and scattering theory for prediction of composite properties.

The research areas of the division's professional staff are indicated with each task and detailed in the following staff list. In addition to publishing eighty papers and twenty-two special reports and books, these highly qualified scientists are also leaders in professional societies, conference organizers, invited speakers, and contributors to collaborative research programs with industries and universities, as documented in the concluding section.

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FRACTURE AND DEFORMATION DIVISION (430)

R. P. Reed, Chief
H. I. McHenry, Deputy Chief
R. A. Schmeit, Administrative Officer
J. M. Bean, Secretary
B. A. Stevenson, Secretary
J. A. Vaughan, Secretary

The principal goal of the Fracture and Deformation Division is to establish the scientific basis to minimize material failure. The materials we study are primarily structural alloys, composites, and weldments. Improvement in mechanical performance of materials is achieved in three ways:

1. Theory and modeling of deformation and fracture, which lead to a fundamental understanding of the mechanisms of material mechanical response.

2. Characterization of mechanical performance, which is essential for the proper development and selection of materials for service applications and for efficient design that takes full advantage of material performance.

3. Development and application of fracture mechanics, which provide quantitative assessment and standards for the integrity of critical structures by relating material properties to flaw characterization and service environment.

A recent study by our division concluded that in the United States costs of over $119 billion per year are associated with fracture. Design, structural codes and standards, material processing, quality control and inspection, and the replacement, inconvenience, injuries, and deaths from unexpected failures contribute to this cost. Our research in fracture mechanics for improved prediction of structural performance from laboratory tests, nondestructive inspection for efficient quality control and defect evaluation, and material processing for reduction of property variability will have a significant effect on the economy of our country.

The technical outputs of the division assist many government agencies, especially the Departments of Energy, Transportation, Defense, and Interior and the Nuclear Regulatory Commission. Our contributions to fusion energy research include low-temperature studies on austenitic stainless steels and composites for structural containment of the large magnetic fields produced by superconducting magnets, study of high-temperature deformation and crack growth, and the development of unique spectrum-loading fatigue capabilities to study structural steels in an ocean environment. Transportation-related research includes: Mechanical-property and microstructural characterization and nondestructive inspection of steels for pressure-tank cars and railroad wheels, fracture-mechanics assessment of tank-car behavior, and numerous structural-metal fracture analyses. Research for the Department of Defense is diverse: We assist in upgrading Navy fracture-control plans, study the fracture and elastic characteristics of new silicon-carbide aluminum-based composites, and conduct large-scale panel tests on high-strength low-alloy steels. Our dynamic crack arrest experiments on 10-m-long test panels have rapidly given us recognition as a large-scale fracture mechanics test laboratory and as a vital component in the national program of Nuclear Regulatory Commission to set crack-arrest standards for the nuclear industry.

Dissemination of the results of recent materials research is an important function of our division. We sponsor a number of workshops and conferences each year (given in the Associated Activities section at the end of this report). We continue to expand and update the Materials Handbook for Fusion Energy Systems and are collaborating with national welding organizations to create a national welding data base.

We have unique mechanical property test facilities with an extensive range of capabilities: temperature - 4 K to 1500 K; specimen size - 200 µm to over 15 m in length; load capacity - 0.2 to 3,000,000 kg. These facilities are also used to meet the needs of researchers from industries, universities, and other government agencies.

Two principal tasks are the guidelines for research of our division:

Task 12123--ELASTIC-PLASTIC FRACTURE MECHANICS commissions the development of elastic-plastic fracture mechanics, the basis for the application of quantitative fitness-for-service criteria to the codes and standards of critical structures, and research in welding and nondestructive evaluation.

Task 12121--FRACTURE MECHANISMS AND ANALYSIS calls for research on fracture physics and mechanical and physical properties in support of advancing technologies and analyses of the causes of major national structural catastrophies.

These tasks are carried out by focusing research on fracture mechanics, nondestructive evaluation, welding, the physics of fracture, time-, structure-, and temperature-dependent processes, composite materials, and elastic properties. These subject areas, reflecting group activities, are discussed in depth in the Technical Activities section.

RESEARCH STAFF

Arvidson, John M.	• Mechanical properties at cryogenic temperatures • Test systems for cryogenics
Austin, Mark W.	• Elastic properties • X-ray diffraction
Cheng, Yi-Wen	• Fatigue of metals • Fracture behavior of surface flaws • Fatigue life predictions
Christ, Bruce W.	• Data-base management • Failure analysis • Mechanical properties
Clark, Alfred V., Jr.	• Ultrasonics (theoretical and experimental) • Engineering mechanics • Applied mathematics
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Hicho, George E.	• Mechanical properties • Ferrous metallurgy
Kasen, Maurice B.	• Low-temperature composites • Grain-boundary kinetics • Failure analysis • Welding metallurgy of aluminum
Kriz, Ronald D.	• Finite element analysis • Mechanics of composite materials • NDE of composite materials
Ledbetter, Hassel M.	• Elastic property modeling and measurement • Composite mechanics • Magnetic behavior of austenitic steels • Physical properties at low temperatures
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- Ultrasonic NDE
- Optical metrology
- High-temperature oxidation and combustion of metals

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- Mechanical and fracture toughness test methods

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- Elastic-plastic fracture mechanics; analysis and test methods
- Mechanical properties of metals

Reed, Richard P.
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- Low-temperature materials
- Martensitic transformations

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- Metal processing

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- Low-temperature physics

Tobler, Ralph L.	• Fracture mechanics • Low-temperature fatigue crack growth resistance • Low-temperature test standards
Walsh, Robert P.	• Mechanical properties • Design and development of mechanical test equipment

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ELASTIC-PLASTIC FRACTURE MECHANICS
Task 12123

This task addresses establishment of a scientific basis for the development of fracture prevention requirements for structural materials that exhibit plastic fracture behavior. Safety and durability are primary considerations in the design and construction of engineering structures. Sophisticated methods to assess structural safety and durability have been developed on the basis of linear elastic fracture mechanics. These analytical methods are applicable to the high-strength alloys used for aerospace vehicles and to the heavy-section steels used for nuclear pressure vessels. Unfortunately, the methods of linear elastic fracture mechanics do not apply to a wide range of metal structures, including bridges, pressure vessels, ships, offshore structures, and pipelines, because in these applications, the materials of construction (steels and aluminum alloys are typical) are highly plastic (nonlinear) before fracture. Consequently, the assessments of structural safety and durability are based on empirical methods and prior experience. Although current methods usually provide a reasonable record of structural safety, improved efficiency and productivity could be achieved if more rational methods were used to establish material-toughness requirements, allowable stress levels, minimum service temperatures, and weld-quality standards.

Modeling of critical structures to assess their fitness for service requires knowledge of the mechanical properties, flaw sizes, and operating stresses of the structural materials and welds. Fundamental knowledge is also required to determine the effects of these parameters on crack initiation and growth to construct quantitative relationships. This task combines the studies of elastic-plastic fracture toughness, fatigue, nondestructive inspection, stress analysis, and welding to develop the science of elastic-plastic fracture mechanics.

FY 85 Significant Accomplishments

- Using the technique for direct experimental measurement of the J-integral for plastic strain fields (developed at NBS), measurements were made on cracks in a series of single-edge-cracked tensile panels and four-point-bend bars made from a high-strength low-alloy (HSLA) steel. The results clearly show that the coefficient of the relationship between the J-integral, plastic strain, and crack size for infinitesimal cracks is near 2. This agrees with predictions based on analytical continuation of the well-known linear elastic relationship among J, elastic strain, and crack size. In contrast to the linear elastic case, the results for plastic strains showed that significant deviations from the basic relationship can occur for small, but not infinitesimal, crack sizes.

- Electromagnetic-acoustic transducers (EMATs) have been used to capture ultrasonic signals forward- and back-scattered from weldment defects. The signals have been processed by two (different) algorithms and related to flaw sizes; the flaw sizes were in the critical range for fracture mechanics (1-4 mm). A sizing accuracy of better than 1 mm was obtained, which is superior to conventional ultrasonic techniques.

- EMATs have also been used in conjunction with a highly accurate ultrasonic velocity measurement system to measure small changes in velocity due to stress. The system was first calibrated on a specimen with a known state of residual stress and then used to measure residual stresses due to welding of thin aluminum alloy plates. Since material anisotropy (texture) causes velocity changes, which can be as large as those due to stress, a simple method has been devised to separate the influences of texture and stress.

- An eddy current probe based on a superconducting quantum interference device (SQUID) has been fabricated for use in measuring the size of small flaws, such as surface-breaking fatigue cracks. A novel method for calibrating eddy current probes (and associated electronics) has been devised, as well as a method of mapping out the electromagnetic field of the probes. The probes have been used to measure perturbations in the electromagnetic field due to small cracks of various sizes and shapes. Measurements were compared with predictions based on a theory developed in a collaboration with Stanford University.

- The capability of conducting threshold fatigue measurements at liquid helium temperature has been established in our laboratory; it is now one of two in the world with this capability. Our automatic computer-controlled apparatus can measure fatigue crack growth rates from 10^{-6} to 10^{-10} m (less than one lattice spacing) per load cycle in the temperature range 295 to 4 K.

- Random-load corrosion fatigue test results and analysis confirmed the adequacy of the root-mean-n averaging method of deriving the equivalent-stress range for fatigue crack growth rate calculations. The value of equivalent-stress range varies with the bandwidth of the power spectrum of load and the exponent in the fatigue crack growth rate equation. Solutions for direct conversion from power spectrum to equivalent-stress range have been developed.

- The evaluation of a matrix of gas metal-arc welds based on a type 308 stainless steel composition has clarified the effect of manganese and nitrogen additions on the cryogenic strength and impact toughness. The addition of nitrogen was found to increase the 4-K yield strength linearly from 600 MPa to 1300 MPa and decrease the 76-K lateral expansion from 0.7 mm to 0.1 mm. Manganese had no effect on the yield strength but decreased the lateral expansion. The data suggest a new term for the commonly accepted formula for calculating ferrite-austenite stability in the welds. Manganese and nitrogen were found to interact, and both first- and second-order terms were necessary to model the interaction accurately.

Fracture Mechanics
Subtask 1 of Task 12123

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[1]Guest Worker, Norwegian Institute of Technology
[2]Guest Worker, Colorado State University

Fracture toughness

Our studies focus on (1) the growth of cracks by fatigue, (2) the relationship between crack size, applied stress or strain, and the static and dynamic driving force for fracture, (3) static and dynamic fracture toughness, and (4) applications of fracture mechanics to assess the safety of real-world structures and to investigate causes of failure.

Fracture mechanics relates the fracture resistance of a material containing a crack to the stress and strain fields in the vicinity of the crack. Fracture occurs when the crack-tip strain fields reach a magnitude that exceeds the material's resistance to fracture. Determination of the critical conditions is complicated by the numerous variables that influence the fracture process. Because modern structural metals are sufficiently tough that fracture rarely occurs under linear elastic strain conditions, we have concentrated on fracture under conditions of plastic strain at and near the crack tip.

A common relationship among J-integral, crack size, and plastic strain has been experimentally verified for small cracks in homogeneous, isotropic metals. Several model predictions for such a relationship are found in the literature; the predictions agree on the form of the relationship: J is proportional to crack size and strain. The predictions disagree on the coefficient, with values from 2 to 5 predicted. Using the technique for direct experimental measurement of the J-integral for plastic strain fields (developed at NBS), measurements were made on cracks in a series of single-edge-cracked tensile panels and four-point-bend bars made from a high-strength low-alloy (HSLA) steel. Cracks sizes up to 3.5 percent of specimen cross section were used. The data were corrected to eliminate finite-crack-size effects that persisted even for the small crack sizes used. The normalized corrected data for the tensile and bending specimens contain some scatter because of experimental difficulties, material inhomogeneities, and so on. The results clearly show that the coefficient of the relationship between J, plastic strain, and crack size for infinitesimal cracks is near 2. This agrees with predictions based on analytic continuation of the well-known linear elastic relationship among J, elastic strain, and crack size. In contrast to the linear elastic case, the results for plastic strains showed that significant deviations from the basic relationship can occur for small, but not infinitesimal, crack sizes and because of special characteristics of the material stress-strain behavior, such as Lüders bands. These results will allow more accurate assessment of the fracture resistance of structural components fabricated from modern tough steels that are capable of substantial plastic deformation before fracture. The behavior was found to be independent of specimen orientation, loading mode, crack size, and temperature.

A set of six four-point-bend fracture tests was completed on wide, thick steel plates. The plates, prepared with fatigue-precracked surface flaws of two lengths, were tested between -40°C and room temperature. The apparent ductile-brittle transition temperatures for these plates were higher than those of small specimens. Lengthening the surface crack also raised the transition temperature. The tests showed that the prominent, presently accepted method of predicting fracture under elastic-plastic strain becomes quite conservative at high plastic strains, especially for the shorter of the two surface flaw lengths tested.

Full-field strain measurements yielded a J-integral for several paths in a plastically strained specimen using a new video-optical technique. The capability of obtaining all in-plane strain tensor components, including the rigid body rotation, and calculating the J-integral from these values allows experimental study of the path dependence of J-integral for actual material stress-strain behavior. The experimental path independence of the J-integral seems to be an indicator of the quality of the strain data. Path independence was found for good data, not for poor data. So far, the data quality has been judged only from the photographic negative of the specimen and grid from which the strain data are obtained. The full field strain data also allow verification of finite-element analysis computer programs commonly used to calculate plastic strains around crack tips.

A double-tension specimen crack-arrest test with controllable load-train compliance and temperature gradient has been developed. From it the temperature and stress intensity factor at which a stressed plate arrests a running crack can be determined, and the effects of stress, temperature, and loading compliance on crack arrest and reinitiation can be studied. Use of this specimen provided additional data on the behavior of the apparent critical stress intensity factor for crack arrest, K_{Ia}, as a function of temperature. Speculation has centered on "the wall," the apparent tenfold rise of K_{Ia} at 40 to 60°C. The amount of plasticity at the crack tip is believed to play a key role in the cause of the "wall" behavior.

Fitness for service

The practical success of a metal structure depends on finding the proper balance between its quality and performance. If quality is excessive, so are costs; if quality is insufficient, failure occurs. the cost-of-fracture study performed recently under the sponsorship of this division showed that the annual cost of fracture in the United States can be reduced by approximately $100 billion by more accurate specification of the quality levels needed in various metal structures. This extra $100 billion is not an insurance cost; it is simply a cost of inefficiency brought on by lack of a complete fracture control strategy.

The fitness-for-service studies develop the fracture mechanics needed for the technical foundation of any fracture control strategy, whereby we can mathematically relate material toughness, tolerable flaw size, and applied stress and strain. Fitness-for-service activities recently have focused on pressure vessels. The crack-driving forces for flaws at various high-stress locations in ship boilers have been calculated to assist in repair decisions. At the request of the U.S. Occupational Safety and Health Administration (OSHA), the division is investigating the probable cause of the failure of a steel pressure vessel that exploded on July 23 at an oil refinery near Chicago, killing seventeen people and causing damages exceeding $100 million.

Fracture mechanics symposium

The Fracture and Deformation Division organized the ASTM Eighteenth National Symposium on Fracture Mechanics, which was held June 25-27, 1985 at the University of Colorado in Boulder. The program included six invited lectures and seventy-four contributed presentations on elastic-plastic fracture mechanics, fatigue, analysis, micromechanisms, crack arrest, applications, ductile-brittle transitions, J-integral test methods, and subcritical crack growth. Significant advances were reported concerning the microstructural, statistical, and geometrical roots of the ductile-brittle transition in steels and their practical consequences.

Fatigue crack growth

Crack initiation and growth under repeated loading is another key technological fracture problem; it also is not thoroughly understood on a first-principles basis.

Recent research has focused on pseudorandom fatigue loading, such as that provided by ocean waves. Load-cycle-interaction effects are defined to be zero for constant-amplitude sinusoidal loading. However, load-amplitude changes have been shown to produce transients in crack growth rate. Retardation after lowering the amplitude is especially easily demonstrated. This effect raises the question of load-cycle interaction effects during pseudorandom loading, in which each cycle usually differs from the previous one.

Studies of random-load fatigue led to a method for calculating flaw growth in structural components subject to random loads. The required inputs are initial flaw size, the power spectral density function that describes the applied loads, and the parameters that describe the material resistance to fatigue crack growth. The description of such phenomena must naturally be couched in statistical terms. Rules for counting cycles and averaging their amplitudes must be specified. The results have shown that by defining one cycle as the maximum load range among three successive mean crossings and by using the material's Paris-law fatigue crack growth rate exponent, n, in a root-mean-n averaging method, cycle-interaction effects are found to be too small to observe, either because they actually are small or because they cancel out over the course of the test. Small cycle-interaction effects were found both in specimens tested in laboratory air and in 3.5 percent saltwater.

It was found that the root-mean-n value of load spectrum with a given power, that is, the root-mean-square value of load amplitudes, decreased with increasing irregularity of the load spectrum and decreasing n in the fatigue crack growth rate equation. The use of the root-mean-n method has been facilitated by the development of correction factors that account for the influence of the irregularity factor of the power spectrum of load and the exponent in the fatigue crack growth rate equation.

For the purpose of experiment and detailed analysis, a computer program incorporating the Monte Carlo technique has been developed to simulate the random signals digitally from power spectra characteristic of the North Sea environment. Random-amplitude fatigue tests conducted with an automated fatigue test facility validated the empirical root-mean-n equation.

Fatigue cracks are believed to grow only when the cyclic stress intensity factor is higher than some threshold value characteristic of the material. The capability of conducting threshold fatigue measurements at liquid helium temperature has been established in our laboratory; it is now one of two in the world with this capability. The principal difficulty in threshold fatigue measurements at low temperatures is the very low crack growth rates involved. Our automatic computer-controlled apparatus can measure fatigue crack growth rates from 10^{-6} to 10^{-10} m (less than one lattice spacing) per load cycle in the temperature range 295 to 4 K. It consists of a servo-hydraulic test machine, a vacuum-insulated cryostat, a minicomputer, and a liquid-cryogen-level control system (see Fig. 1). The computer systematically decreases the test loads according to a programmed formula to protect the measured growth rates from errors that might result from too-rapid load reductions. A typical test cycles a 6.4-mm-thick specimen at a frequency of 40 Hz for 4 days, 24 hours a day, for a total of 13×10^6 fatigue cycles.

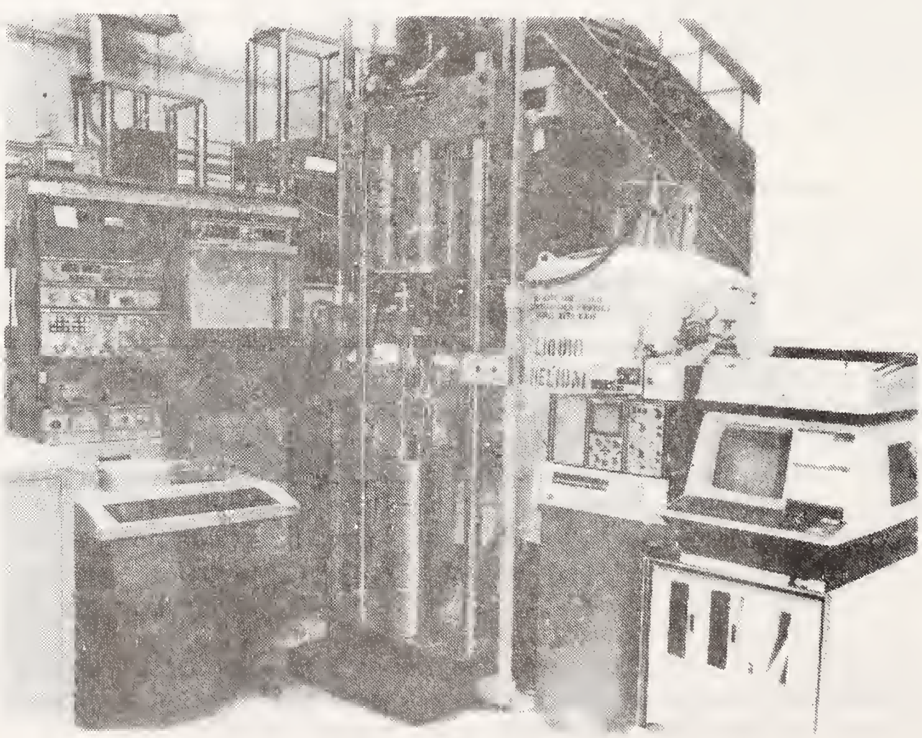

Fig. 1. Automatic fatigue testing system.

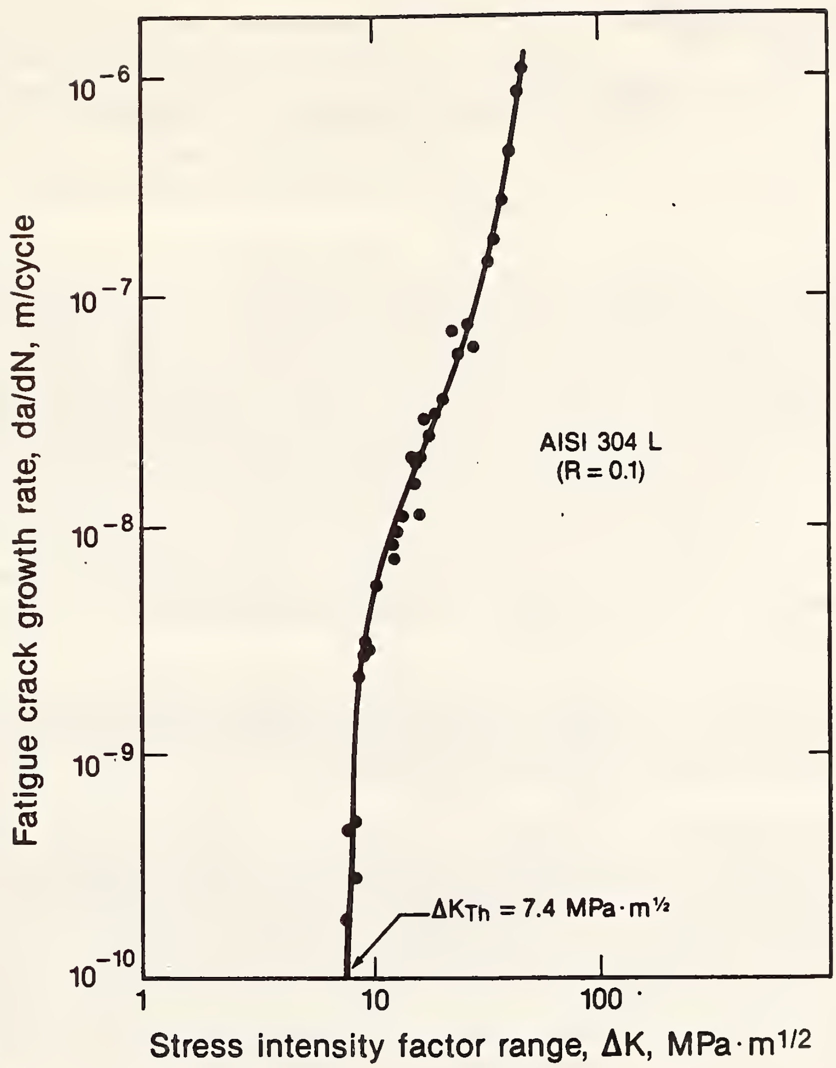

Fig. 2. Fatigue crack growth rates and threshold stress intensity factor for AISI 304L stainless steel at 4 K.

Using this test apparatus, we have measured very low rates of crack growth, below 10^{-8} m/cycle, which were then used in extrapolations to find the threshold value of the stress intensity factor, ΔK_{Th}. The data for six austenitic stainless steels have been obtained at 295, 76, or 4 K. Typical results for AISI 304L are shown in Fig. 2. The results at 4 K have been analyzed and a correlation was obtained: ΔK_{Th} increases as the material's tensile yield strength increases. This correlation and others are being pursued because they offer the possibility of predicting the behavior of untested alloys. Results to date indicate no threshold at 295 K down to a growth rate of 10^{-10} m/cycle, and threshold behavior at 4 K below about 10^{-9} m/cycle.

A new apparatus for measurement of low-cycle fatigue lives of metals at 4 K will soon be in operation. This apparatus, supported by outside funds, will be used to test materials for the space shuttle.

Nondestructive Evaluation
Subtask 2 of Task 12123

A. V. Clark, Jr., J. C. Moulder, R. E. Schramm, P. J. Shull, T. A. Siewert, D. Mitraković[1]

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A primary function of this group is the development of improved methods for detecting and sizing significant flaws in weldments. The ability to size flaws rapidly and accurately is essential to the assessment of structural integrity by fitness-for-service concepts using fracture mechanics. Historically, nondestructive inspection of weldments has been conducted by radiography with workmanship as the criterion. However, radiography has serious deficiencies when applied in a fitness-for-service approach. It lacks sensitivity to the most critical two-dimensional, planar flaws, such as cracks or lack of fusion; it does not readily lend itself to measuring the through-wall depth of flaws, which is the most significant dimension from a fracture mechanics point of view.

A more promising approach is provided by ultrasonic techniques. Advantages are a high sensitivity to significant planar flaws combined with a potential for providing the required sizing information.

Most ultrasonic inspection techniques have used high-frequency longitudinal or vertically polarized shear waves transmitted from a piezoelectric crystal. Although this has worked reasonably well as a flaw detection tool, it is unable to provide flaw sizing information with the required accuracy and speed. A primary problem is the difficulty of discriminating the flaw signal from the many spurious signals created by variations in weld geometry and by mode conversion of the ultrasonic wave. This approach also requires use of a coupling agent between the crystal and the workpiece, making it slow and difficult to apply under field conditions.

The group is therefore pursuing an alternative approach--the development of an inspection method using electromagnetic acoustic transducers (EMATs) operating at low frequencies and using a shear horizontal (SH) wave as the ultrasonic probe. In principle, this approach is capable of overcoming most of the deficiencies associated with conventional high-frequency systems. The transducer is noncontacting, the flaw signal is less ambiguous, and the system is capable of being automated.

The theoretical basis for this approach has been developed and validated. Additional improvements in sizing capability have been obtained by the use of algorithms other than just the amplitude of the back-scattered ultrasonic signals in the time domain. Work is now continuing to determine the optimum signal analysis techniques and to validate the approach for real flaws in weldments.

The group is also developing EMAT techniques for determining the state of residual stress in weldments. The principle is to generate horizontally polarized SH waves that propagate through the specimen. Small stress-induced changes in phase velocity are measured with a highly accurate and precise velocity measurement system and related to components of the (plane) stress tensor. Because material anisotropy (texture) also causes changes in velocity, it has been necessary to develop methods to separate the influences of texture and stress. These methods have been tested on both a calibration specimen and on welded aluminum alloy plates.

There is also interest in developing eddy current techniques for detection and characterization of small surface flaws. This involved the design of a broadband eddy current probe to permit detection of very small flaws in high-resistance aerospace alloys. Probes have been constructed and used to measure signals from simulated and real flaws to validate theoretical models of the probe-flaw interaction developed at Stanford University. Recently we have added the capability for computer-controlled positioning of the eddy current probe to study probe behavior in a scanning mode of operation.

Electromagnetic-acoustic transducers: sizing weldment defects

Our work on nondestructive evaluation using ultrasonics has formerly centered on the development of electromagnetic acoustic transducers (EMATs), the analog electronics they require, and the theory necessary to understand and interpret the scattering properties of long wavelength, SH waves.

Our new approach to flaw sizing utilizes three EMATs, arranged as shown in Fig. 3. One transmitting EMAT generates signals that are forward- and back-scattered by the flaw and received by EMATs R_1 and R_2, respectively. Features associated with these signals (e.g., amplitude and power) are extracted for use in flaw sizing. To date, we have had success in sizing by using either the ratio

$$\frac{\text{forward-scattered power}}{\text{back-scattered power}}$$

or

$$\frac{\text{forward-scattered amplitude}}{\text{back-scattered amplitude}}$$

Calibration curves based on these ratios were generated on artificial defects (saw cuts) of varying depth; a typical calibration curve is shown in Fig. 4.

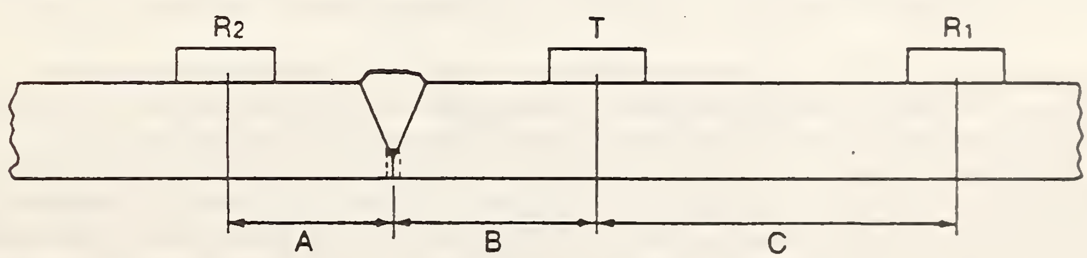


Fig. 3. EMAT array for flaw sizing.
T = transmitter, R_1 = receiver for back-scattered signal,
R_2 = receiver for forward-scattered signal.

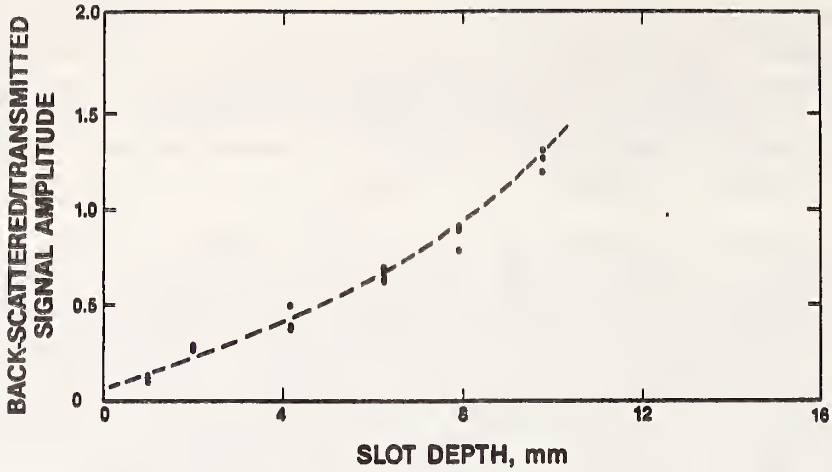
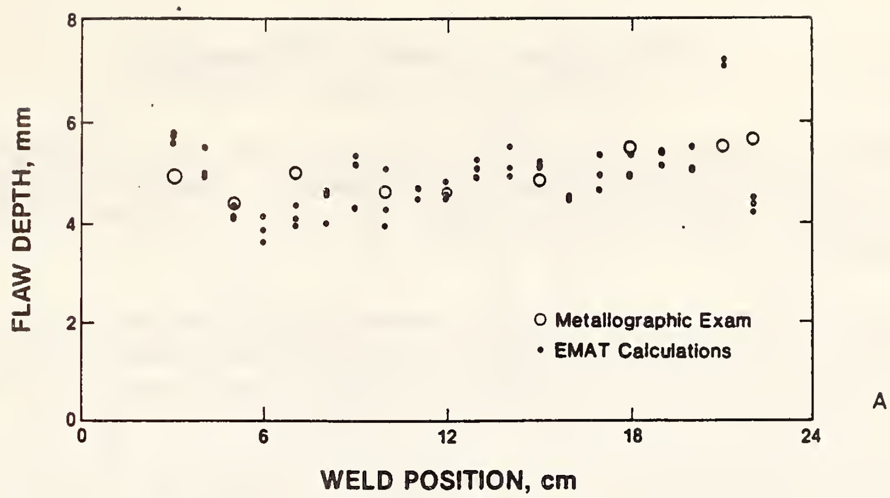


Fig. 4. Calibration curve gathered with artificial defects in A516 steel. Curve is based on amplitude ratios.

Real defects due to inadequate penetration were produced by our in-house Welding Group; defects ranged in size from 2 to 7 mm. The weldments were scanned by the EMAT array, the ultrasonic signals were recorded, and flaw sizing was done using the calibration curves. Destructive measurements were then performed and the actual flaw sizes (depth) obtained. Good agreement between ultrasonic and destructive measurement was obtained, as shown in Figs. 5a and 5b; the former was obtained using amplitude ratios, and the latter using power ratios. It appears (based on statistical analysis of the data) that the former may be slightly more accurate. However, either method gives an accuracy of ±1 mm or better.

Inadequate penetration results in cracks that are normal to the plate surfaces; these cracks are easy to detect with SH waves, which are guided by the plate and strike the cracks at normal incidence, resulting in a large scattering cross section. We are now studying the more difficult problem of sizing of inadequate fusion defects, which result in canted cracks at the interface between weld and base plate. The fact that these cracks are canted results in a smaller scattering cross section and a more complicated wave form. A computer program (developed at University of Colorado) is being used to simulate the interaction of ultrasonics with a canted crack in a plate. The results of this computational study will be used to develop the optimum EMAT array configuration for sizing of inadequate fusion defects.

The recent addition of a welding research program to the division has stimulated interest in applying EMAT technology to the problem of detecting flaws during automatic welding operations. Successful development of a method to detect flaws as they are produced during the welding operation would provide two important benefits: First, it could be used to monitor the quality of the weld to ensure proper operation of an automatic welding system (this is particularly important in fully automatic welding, where the ability of an expert welder to compensate for changes in joint geometry or arc characteristics is lacking). Second, it could substantially reduce the costs of weld repair by limiting grinding and rewelding of a defective weld to the pass in which the flaw occurred.



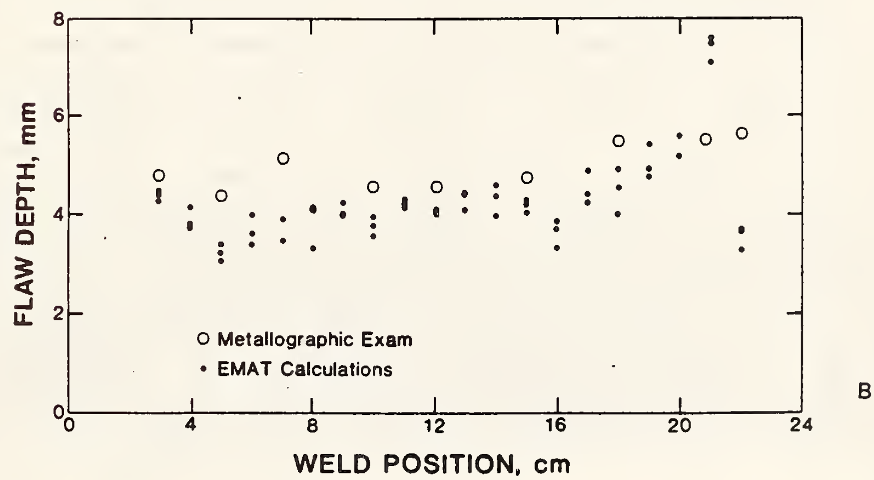


Fig. 5. Comparison of EMAT and metallographic (destructive) measurement of real weldment defects. EMAT measurements used calibration curve based on amplitude ratios (A) and on power ratios (B).

EMATs are particularly well suited to this application by virtue of their ability to operate on rough, unprepared surfaces without the need for coupling agents, to discriminate against other types of acoustic waves (longitudinal or shear-vertical), and to operate at long wavelengths.

Experiments are underway to determine the ultrasonic characteristics of partially completed welds to assess the feasibility of an EMAT-based approach to real-time weld inspection. Future studies will examine partially completed welds containing flaws to determine detectability thresholds. We plan to operate the EMAT inspection system during actual welding operation to assess the effect of electromagnetic interference from the welding arc on the electronic circuits associated with the EMAT system.

Electromagnetic-acoustic transducers: residual stress measurement

The presence of residual stress due to welding can have a significant influence on the fracture toughness of a weldment. Hence, it is important not only to be able to size weldment flaws, but also to characterize the state of residual stress.

Ultrasonics is a promising tool for nondestructive measurement of residual stress. For metals, the presence of stress causes a small, second-order change in sonic velocity; the highly accurate electronics of today make it possible to measure these changes (typically within 10-100 ppm).

Unfortunately, the presence of anisotropy (texture) due to material processes such as rolling and extrusion can also induce changes in sound speed. Consequently, methods of separating the influence of texture and stress are of great interest to researchers in ultrasonic stress measurement.

A simple, yet highly accurate and precise, velocity measurement system has been developed. The system can be used with either conventional ultrasonic transducers or with EMATs. A specimen with a known state of residual stress was used to calibrate the system. The specimen consists of an oversize stainless steel plug inserted in a hole in an aluminum alloy plate; see Fig. 6. Measurements of the acoustic birefringence, B, (normalized difference in phase velocity of orthogonally polarized SH-waves) were made with EMATs. The difference between the acoustic birefringence in the stressed state (B) and the unstressed state (B_o) is proportional to the difference of principal stresses: $B - B_o = m(\sigma_1 - \sigma_2)$, where m is the stress-acoustic constant for the material and σ_1 and σ_2 are principal stresses.

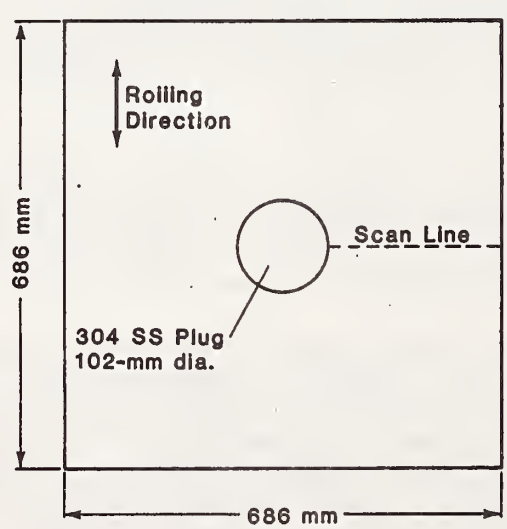


Fig. 6. Residual stress specimen used to calibrate velocity measurement system for ultrasonic stress measurement.

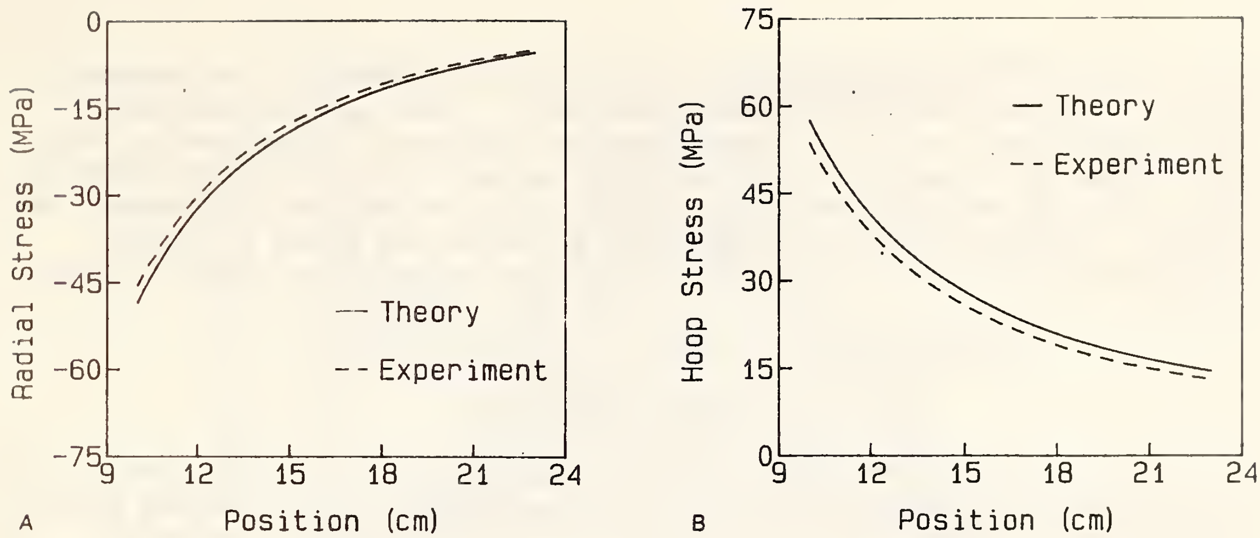


Fig. 7. Residual stress specimen: (A) Radial stress; position is measured radially from center of stainless steel plug. (B) Hoop stress.

In the specimen shown in Fig. 6, the values of B_o along the scan line (where ultrasonic data were taken) are not known. However, the corners of the plate are stress-free. The value of B_o was measured at multiple locations in the corners, and the average value was used to approximate values of B_o along the scan line; measuring multiple values and averaging supresses the effect of material inhomogeneity. For the axisymmetric stress state in the specimen, the difference of principal stresses can be integrated to obtain radial and hoop stresses. The experimental values are in excellent agreement with theoretical values, as shown in Fig. 7.

Residual stresses due to welding of thin aluminum alloy plates were measured with two techniques using EMATs. In the first technique, EMATs are used as "ultrasonic strain gages;" that is, the time of flight of orthogonally polarized SH waves was measured with EMATs before and after welding. Because EMATs require no coupling agent (with corresponding variations in acoustic path length), changes in arrival times are related to principal stresses, provided that (a) stresses are in the elastic range and (b) no change in microstructure occurs. Residual stresses outside the heat-affected zone were measured with this technique and were within about 20 MPa of strain gage measurements.

In the second technique, the shear stress is measured and related to normal stresses by the equations of stress equilibrium. This technique has the advantage of being less sensitive to the influence of texture. Shear stress gradients were measured starting at the (free) edge of the welded plates and working inward toward the weld. These gradients were integrated (in accordance with stress equilibrium) to obtain the stress acting normal to the weld seam. Values thus obtained were also within 20 MPa of gage values. This compares quite favorably with the level of stress accuracy obtainable with conventional bulk residual stress measurement techniques, such as (destructive) hole drilling.

For a fracture mechanics assessment of structural integrity, the stresses acting on a flaw must be determined absolutely. Most current ultrasonic stress measurement techniques measure either the sum or difference of principal stresses, relative to some (unknown) stress level. It is necessary to remove the influence of texture so that absolute determination of stress can be made. The measurements reported here are among the first to obtain welding residual stresses absolutely, with good stress resolution (20 MPa or better).

Eddy currents

Sponsored by the NBS Office of Nondestructive Evaluation, our program on eddy current characterization of surface flaws has addressed the unsolved problem of quantitative inversion of eddy current signals to obtain flaw sizes. Experimental studies at NBS were carried out in collaboration with B. A. Auld of Stanford University, who is developing theoretical models of the probe-flaw interaction. The emphasis of the experimental program was to provide accurate, well-characterized eddy current measurements on actual and simulated flaws to validate the theoretical models.

As part of this effort, a computer-controlled eddy current scanner has been built and is now in operation. The scanner can be used with a variety of probe designs. The eddy current scanner is equipped with a computer-controlled positioner and automatic data acquisition to permit rapid, accurate measurements of flaw signals. The scanner is now being used for measurements on a series of calibration flaws for input to the modeling effort. The output of several scans made of a simulated flaw in a highly conductive material is shown in Fig. 8. The magnitude of the impedance change, ΔZ, of the nonuniform field probe (due to presence of the flaw) is shown for a variety of frequencies, as well as theoretical predictions. As can be seen from the figure, there is good agreement between theory and experiment.

Comparisons of theory and experiment in eddy current testing have been extended to low-conductivity materials this year. Experimental flaw scans were obtained for both EDM notches and fatigue cracks in Ti-6Aℓ-4V using air core and ferrite core probes. The results were compared to predictions of the Stanford theory. This is an important step in establishing the validity of the present probe-flaw interaction theory, since the theory assumes perfect conductivity in order to calculate magnetic field inside the flaw (finite specimen conductivity is introduced later, in evaluating the electric field inside the flaw). Past studies have been limited to highly conducting materials, such as aluminum.

Another related experimental study addressed the problem of calibration methods for eddy current measurement systems. Quantitative inversion of eddy current signals to obtain flaw sizes requires knowledge of the absolute magnitude and phase of the change in probe impedance caused by a flaw. Most commercial eddy current systems only provide relative measures of this impedance change. A new calibration method for uniform-field eddy current probes has been devised and tested in collaboration with B. A. Auld of Stanford and E. Smith of Pratt and Whitney. The method consists of measuring

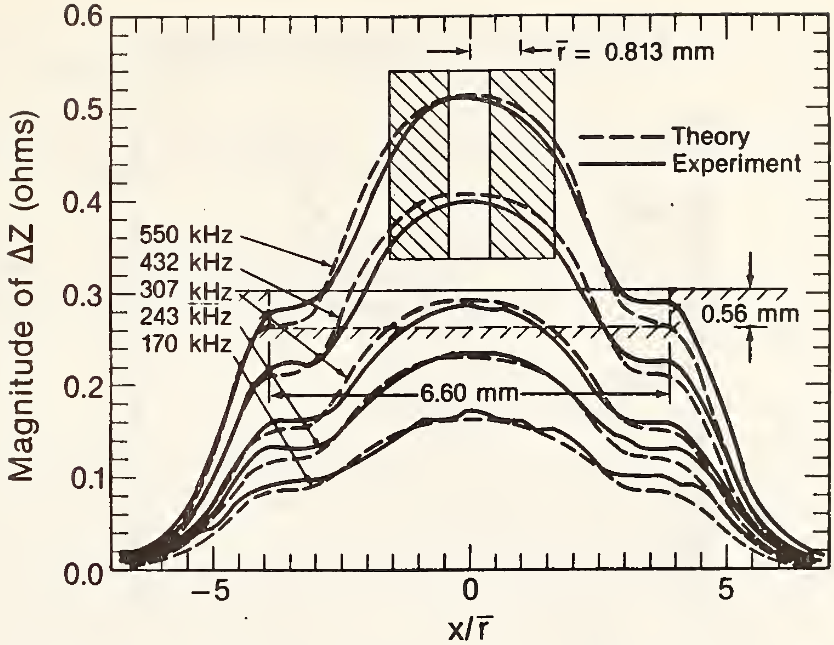


Fig. 8. Magnitude of impedance change, ΔZ, determined by scanning of EDM notch in Aℓ 6061. Theoretical curves were calculated from the nonuniform field probe-flaw interaction theory.

the impedance change induced in a probe by a cylindrical recess of known volume in the surface of a specimen of known conductivity. The quantities can be related to the value of H/I for the probe, the field strength per unit current. The latter quantity enters into any calculation of flaw signals for the probe.

A unique study on the influence of a probe's magnetic field on flaw signals was carried out in collaboration with T. Capobianco and F. Fickett in Division 724 and B. A. Auld at Stanford. The magnetic fields of three eddy current probes were mapped using techniques developed in Division 724. For two nominally identical air core probes, measured field distributions were compared with those predicted by the Stanford implementation of theory. Differences of up to 40 percent in the flaw signals produced by these probes for identical flaws were traced to a 10 percent difference in the probes' field strengths. For a different ferrite core probe, the experimentally obtained field profile was used as an input for calculating flaw signals using the Stanford nonuniform field probe-flaw theory. Calculated flaw signals were in good qualitative agreement with measured flaw profiles.

Methods for growing fatigue cracks in a predictable, reliable fashion have been developed and proven. We have shown that a reflection-type eddy current probe can be used to monitor the growth of the crack rather than the customary crack mouth opening displacement (CMOD) gage, which is less sensitive and requires very large starter notches. The reflection probe used was demonstrated to have an output that is linear with flaw cross-sectional area; see Fig. 9. The length of the flaw can be determined by scanning the probe along the length of the flaw. Having the length and area of the flaw permits determination of the depth more reliably than can be done from CMOD measurements.

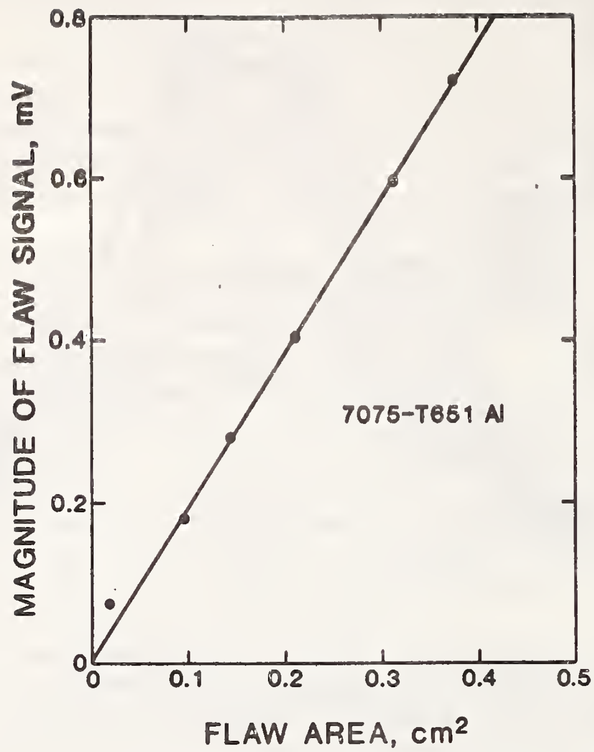


Fig. 9. Magnitude of flaw signal during growth of fatigue crack in Aℓ 7075-T651 as function of cross-sectional area of crack.

Optical determination of two-dimensional strain fields

A new technique for measuring and displaying two-dimensional strain fields in test specimens has been developed. In the past, quantitative determination of entire strain fields has been hampered by the laborous time-consuming analysis required by existing techniques, such as moiré analysis or photoelastic coatings. In common with moiré analysis, the new method requires fine grids to be applied to the surface of object under study; however, the method of analysis is completely different. Photographs are taken of the specimen grid in both the undeformed and deformed states. The photographic negatives are then analyzed by passing a laser beam through the negative and forming a diffraction pattern with a positive lens. The diffraction pattern is imaged with a solid state video camera and the image is digitized and stored with a video digitizer. A desk-top computer interfaced to the digitizer determines the locations of the first-order diffraction peaks in the image and compares these with the locations of diffraction peaks for an undeformed specimen grid. This analysis yields all four in-plane components of the deformation tensor: longitudinal strain, transverse strain, shear strain, and rigid body rotation. These qualities are necessary to evaluate the J-integral, a parameter which characterizes a material's fracture toughness. Evaluation of the entire deformation field is accomplished by analyzing the photograph point by point, a task that can be readily automated. The usefulness of the technique for fracture mechanics studies has been demonstrated by obtaining the J-integral in a series of tests on cracked tensile panels of aluminum.

Welding
Subtask 3 of Task 12123

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[3]Guest Worker, Armament Development Authority of Israel

Welding laboratory

Welds are a key consideration in determining the fitness for service of a structure because failure often originates at such locations. The presence of weld flaws can cause deleterious stress concentrations. The division has long been concerned with flaws in the context of fracture mechanics analysis. To expand our competence in this area, we have established a welding laboratory to facilitate fundamental studies of welding processes, leading to a better understanding of flaw formation and therefore better process control.

The welding laboratory incorporates the latest computerized, real-time, fully adaptive gas metal-arc (GMA) welding system. This equipment is unusual in that all control functions, including seam tracking, are performed by arc sensing. It can be operated in a fully automatic, computer-programmed mode to reproduce a given weldment, or it may be operated in a semiautomatic mode in which operating parameters required for different welds are preprogrammed into the computer. An extremely stable dc power supply designed specifically for welding research is on order to complement this welding system. It permits GMA welding in the pulse mode of droplet transfer using any desired waveform. This equipment will be used for studying arc physics, weld-pool dynamics, and the significance of metallurgical structure on toughness. It will be used to study precursors to flaw formation and to produce highly characterized weld flaws for evaluation by advanced NDE methods.

The laboratory has conventional equipment and power supplies required for welding by the shielded metal-arc (SMA) and the gas tungsten-arc (GTA) processes. The power supplies may be connected in multiple ways to provide a wide variety of volt-ampere response curves. The laboratory is equipped with support equipment for plate cutting and beveling. A variety of shielding gases are manifolded for maximum flexibility of mixture. A special positioner, custom-built for the laboratory, provides the capability of welding in any position from flat to overhead. A 300-kV x-ray source has been installed for radiographic inspection.

The capabilities have been extended by the acquisition of a transistorized current regulator. This filters the electrical noise produced in a conventional welding power supply, leaving a pure dc waveform. Such pure signals are essential for our current study of the fundamental interplay between arc forces and droplet transfer. A new control circuit has been designed and is being installed to allow the simulation of a greater variety of welding power supply volt-ampere response characteristics.

The welding laboratory has been used to produce welds with precisely sized and oriented surface and buried flaws. These flawed welds are being evaluated by the NDE group and compared with optical measurements of the flaw size. Such highly characterized flaws are not available commercially. With further development, they have the potential for becoming reference materials.

Porosity in aluminum alloy welds

We are developing specialized techniques for a systematic study of the mechanisms causing porosity formation during gas metal-arc (GMA) welding of the 5000 series aluminum alloys. At the heart of the system are three precision total mass flowmeters. One controls the main argon shielding gas flow. Another permits us to create desired levels of porosity by metering small quantities (5-15 cm^3/min) of contaminant (hydrogen or propane) into the argon shielding gas during the welding operation. The third flowmeter allows us to add small quantities of chlorine (5-15 cm^3/min) to counteract the influence of the contaminant.

With this equipment, we will be able to establish a quantitative relationship between the amount of contaminant required to produce a given porosity level and the amount of chlorine required to counteract it for a given set of welding parameters. We shall then determine the extent and direction in which this balance is altered by changing the arc characteristics (using the recently acquired transistorized current regulator) and by altering the weld pool dynamics (by systematic changes in welding speed). Additional data will be obtained by analyzing intrinsic changes in the welding parameters associated with formation and removal of porosity (such as arc voltage, amperage, stability, and thermionic emmission). Characteristics of metal transfer across the arc and of the weld pool fluidity and convection modes will be monitored by high-speed cinematography and video.

These data will be analyzed in an attempt to clarify the extent to which porosity formation is due to an interaction between the contaminant and the welding arc and the extent to which it is a phenomena influenced by weld pool dynamics.

Stainless steel weldments

Stainless steel welds generally have excellent fracture toughness but are slightly less tough than the base materials. At cryogenic temperatures this small difference in toughness becomes appreciable. Nitrogen additions, which substantially increase the cryogenic strength of the base material and welds, further reduce the fracture toughness (see Fig. 10). We have evaluated a matrix of stainless steel welds based on a type 308 composition and with independently varying manganese and nitrogen contents. The measured toughness, strength, and ferrite contents of these gas metal-arc welds were compared with existing information and models. This study revealed an unexpected nonlinear relation between strength and toughness and first- and second-order interactions between manganese and nitrogen when both are at high concentrations.

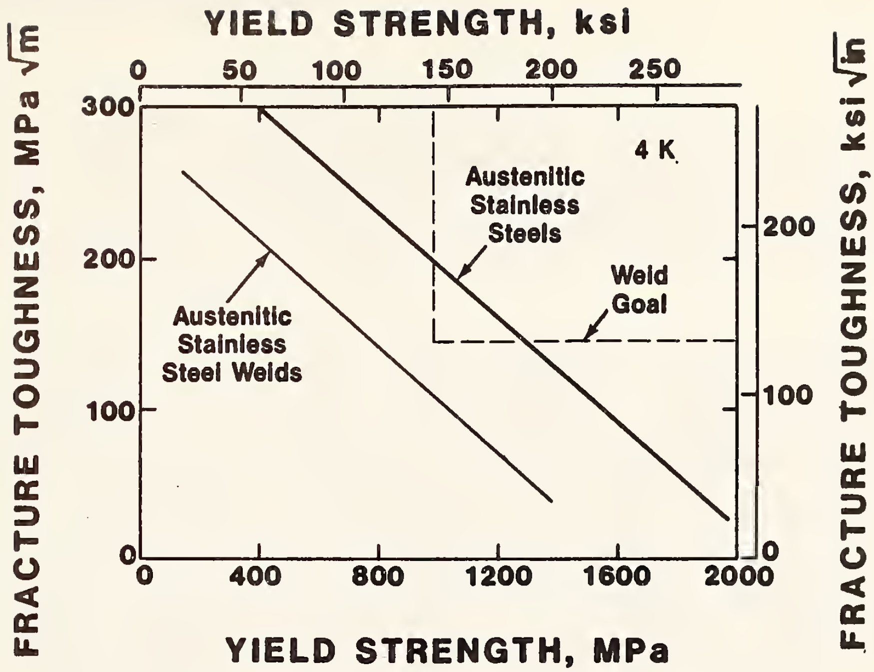

Fig. 10. Comparison of stainless steel base material and weld toughness at 4 K as the strength is increased by nitrogen additions.

FRACTURE MECHANISMS AND ANALYSIS

Task 12121

Our program on fracture mechanisms and failure analysis has a broad spectrum of goals: (1) the development of fundamental theories on crack-tip structure and processes, (2) the characterization of the mechanical and physical properties related to time-, structure-, and temperature-dependent effects on metals and composites, and (3) the application of established methodologies in the analysis of actual failures.

For structural materials, a knowledge of the fundamentals of crack-tip structures and processes is essential to understanding fracture in these materials and to predicting their long-term service life. Influences of atomic structure and chemical reactions at crack tips have been demonstrated with atomistic models of fracture in a solid, but these influences are only beginning to be confirmed quantitatively by experimental studies of subcritical crack growth and environmental effects. Ductile processes in the high-stress region of the crack tip are being introduced into these atomistic models to assess the role of plastic deformation and to extend the theoretical models to describe crack-growth phenomena, such as creep crack growth and fatigue. High-temperature fracture is a complex process with competitive fracture mechanisms, such as subcritical crack growth, cavity nucleation and growth, and grain-boundary sliding; it is affected by microstructure, impurity content and segregation, processing history, and environment. Failure analysis studies perform a valuable service for those government agencies that have no testing facilities and require research on the safety of structural materials. Using metallographic, x-ray, fractographic, and chemical analysis techniques, our division analyzes and compiles data on many critical structural failures.

FY 85 Significant Accomplishments

- New, successful dynamic crack-arrest tests have been carried out in wide plates of nuclear pressure vessel steel. As part of a national program to predict crack growth behavior in nuclear reactors, these measurements have catapulted the Fracture and Deformation Division staff into the forefront of crack-arrest research. Conducted on 10-m long, 1-m wide plate and containing a temperature gradient of up to 300°C across the plate width, these tests represent experiments on the largest specimens ever used. Crack arrests have been achieved and the new data are already being used to suggest changes in national nuclear pressure vessel design codes.

- Fundamental analysis of dynamic cleavage in ductile materials was developed. A critical velocity near that of sound, above which a crack in ductile materials can propagate by cleavage, was derived. General theories of relativistic dislocation shielding of cracks were developed. The dislocation free zone and the plastic zone are found as functions of crack velocity and material properties. When they are combined with a work-hardening law and the Griffith condition at the crack tip, fracture toughness relations are obtained.

- The dependence of strength and toughness on microstructure was investigated as a function of heat treatment and plate thickness in an HSLA steel. The influence of precipitates and grain size were measured separately and quantitatively. A rare type of fracture, star fracture, was observed in this alloy for certain heat treatments. This type of fracture may limit the applicability of this high-strength steel. The causes of this fracture behavior were determined. Efforts are underway to identify heat treatments or thermomechanical treatments to remedy this behavior.

- Recent research on austenitic stainless steels in collaboration with the steel producers is substantially contributing to the development of stronger and tougher alloys for cryogenic service. Major results this year include: (1) interstitial carbon plus nitrogen increase the shear and Young's moduli at 4 K (contrary to their effect at ambient temperatures, where they decrease all the elastic stiffnesses) and increase the stacking-fault energy at room temperatures, (2) interstitial carbon plus nitrogen strongly affect the Néel temperature (contrary to previous reports), decreasing it approximately 15 K per atomic percent interstitial, (3) manganese additions increase the stacking-fault energy of the alloys, (4) nitrogen additions increase the strength but decrease the toughness at 4 K, (5) nickel additions increase the toughness but have little effect on the strength at 4 K, and (6) molybdenum additions increase both toughness and strength at 4 K. These new data have proven encouraging and now new alloys are being produced that have higher nitrogen, nickel, and molybdenum content; they are expected to be strongest, toughest austenitic alloys ever produced.

- Techniques have been developed for laboratory preparation of extremely high-quality, well-characterized organic-matrix composite specimens for research purposes. The method is rapid, inexpensive, and provides complete control over all significant material parameters. Test methodologies optimized for the rod-shaped specimen configuration have also been developed.

- A relationship has been established between the formation of "knees" in the stress-strain diagrams and damage mechanisms in woven-fabric composites tested at cryogenic temperatures. Finite-element models showed that the weave geometry could be beneficial in crack arrest under tensile loading. Damage mechanisms were shown to produce significant changes in mechanical performance at strains well below ultimate failure.

- A fiber optics technique correlating a decrease in light intensity with fiber separation has been developed and applied to the measurement of crack opening displacement between broken ends of single fibers in a composite matrix. This permits a detailed study of the parameters influencing the initial stages of damage accumulation under load.

- The internal strain in an SiC/Al particle-reinforced composite was determined by conventional x-ray diffraction procedures and by an elastic hole-in-the-sphere theoretical model. The combined results demonstrate the existence of hydrostatic stress and establish the key parameters that are required in formulating a plastic deformation model of such materials.

Fracture Physics
Subtask 1 of Task 12121

I.-H. Lin, R. deWit, R. M. Thomson

In the area of fracture physics, the group studies the basic fracture characteristics of materials in terms of the dislocation-crack tip interaction. The initiation and spreading of plastic zones from the crack tips are represented by dislocation pileups generated either from the intrinsic crack tips or external Frank-Read sources. We study three general areas: dislocation processes at quasi-static crack tips, dynamic theory of dislocation-crack interaction, and the role of surface stress in fracture. In dislocation processes at quasi-static crack tips, we develop a dislocation shielding theory for materials under the general loading condition and explore the fracture toughness relationships. Other studies relate to dislocation emission and cleavage processes at quasi-static crack tips. Under general loading conditions, we found that the condition for equilibrium of a cleavage crack involves primarily only the mode I part of the local K-field, although the dislocation emission depends on the full specification of all three components of the local K-field.

In dynamic theory of dislocation-crack interaction, we pursue two approaches: (1) We first develop an analysis for a uniformly moving system consisting of a single dislocation and crack and rederive the dislocation emission and cleavage criteria under conditions in which the crack and dislocation experience only "small" accelerations. (2) We consider the effect of time retardation during the crack-dislocation interaction on dislocation emission. Other studies involve dynamic dislocation shielding. We develop theories of shielded cracks when both crack and shielding dislocation cloud are in fast motion.

In the role of surface stress in fracture, R. Thomson, T.-J. Chang, and I.-H. Lin study the interrelationships between surface stress, free energy, and substrate volume stress and develop line singularity models for simulating the surface stresses on the crack surfaces due to the adsorption of foreign chemical species on the cleavage surface near the crack tip. This study addresses the fundamental problem of environmental embrittlement caused by surface stresses.

An elastic analysis of line singularities interacting with a crack was developed. The line singularities simulate the action of surface stress, which are present on all open surfaces, and which can be modified by adsorption of foreign chemical species on the cleavage surface near the crack tip. When dislocations are included near the crack tip, it is found that under the elastic conditions for a slit crack, these line singularities exert forces on the dislocation and can modify the ductility of materials.

A review was written entitled "Dislocation Concepts Applied to Material Modeling." It gives a selective survey of several research areas where dislocation concepts have made useful contributions to our understanding of the physical world. The value of dislocation theory for interpreting plastic deformation and work hardening is discussed. Although the plasticity of crystalline materials is still not fully understood, the data can be summarized compactly in deformation-mechanism maps. Dislocation concepts have led to elegant continuum theories, which are closely related to differential geometry and have analogies in electrodynamics and relativity. The structural discreteness of the crystal can be modeled with the quasi-continuum and nonlocality. Although atomic models are still needed to treat the core of a defect, they are limited by the computer capacity and the uncertainty of the interatomic potentials. Dislocation concepts are also useful in fields other than solid crystals, namely, surface crystals, liquid crystals, magnetism, amorphous materials, and waves.

Physical Properties
Subtask 2 of Task 12121

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The physical properties studied by measurement, analysis, and review are sound velocities, internal friction, thermal expansivity, specific heat, magnetic susceptibility, volume (mass density), stacking-fault energy, phase transformation, and especially, elastic constants. Many types of materials are characterized: metals and alloys, polymers, intermetallic compounds, ceramics, and composites, which include particle, fiber, and cloth reinforcement and both metallic and nonmetallic matrices. Most of these properties and materials are studied between ambient and liquid-helium temperatures.

Problems of particular interest include: (1) relationships between monocrystal and polycrystal elastic constants, including texture effects; (2) elastic-constant/Debye-temperature interrelationships; (3) relationships between elastic constants and other physical properties: (4) effects on elastic constants of phase transitions; (5) elastic-constant interrelationships; (6) calculations of elastic constants from interatomic potentials, such as the Morse potential and pseudopotentials; (7) models relating macroscopic elastic constants of composites to those of their constituents; (8) models of the physical properties of multiphase systems.

In the thermal-expansivity area, the group has several interests: (1) thermodynamics of thermal expansion, including interrelationships with other physical properties; (2) relationships between thermal expansivity and elastic constants; (3) composite measurements and modeling, which requires the elastic constants; (4) measurements and theory of thermal expansion of fcc metals, especially austenitic steels, which show Invar-related volume-temperature effects.

In phase transitions, the group pursues two approaches: (1) the description of martensite-transition crystallographic features using theories due to Wechsler, Lieberman, and Read and to Bowles and Mackenzie; (2) modeling of phase-transition energetics using interatomic potentials, which includes prediction of cohesive energies, volumes, elastic constants, Debye temperatures, crystal-structure-transition temperatures, and nucleation barriers.

Several important results have been obtained this past year:

1. Results of a study of manganese additions to Fe-Cr-Ni alloys (austenitic stainless steels) indicated that they increase the stacking-fault energy of the alloys.

2. Another study of Fe-Cr-Ni alloys showed that interstitial carbon plus nitrogen increase the shear and Young's moduli at 4 K, contrary to their effect at ambient temperatures, where they decrease all the elastic stiffnesses.

3. In a study of the low-temperature elastic and magnetic properties of Fe-Cr-Ni alloys, we found that, contrary to previous reports, interstitial carbon plus nitrogen strongly affect the Néel temperature, decreasing it approximately 15 K per atomic percent interstitial.

4. The effect of voids on longitudinal sound velocity, v_ℓ, was determined for polycrystalline copper that crept in tension at high temperatures: voids decrease v_ℓ. From theoretical modeling, we deduced that the voids are nonspherical, disc-shaped, and consistently perpendicular to the stress axis.

5. In a study of the effect of low temperatures on elastic constants of Ti-Al alloys, we discovered a low-temperature phase transition that affects shear-mode-related elastic constants. Otherwise, elastic stiffnesses behave regularly, increasing with decreasing temperature.

Time-Dependent Properties
Subtask 3 of Task 12121

R. J. Fields, C. H. Brady, R. deWit, D. E. Harne, G. E. Hicho, S. R. Low, T. R. Shives, L. C. Smith, D. T. Read, J. D. McColskey

Whether fracture occurs in milliseconds, as in the collapse of a hotel walkway, or over a period of years, as in the slow rupture of steam pipes, the time dependence or kinetics of fracture is always important. This group studies the kinetics, rather than the mechanics or energetics, of fracture. Projects include the dynamic fracture of reactor pressure vessels, in which crack growth must be resolved during microsecond time increments, and creep crack growth, in which failure may take years. Although the research is primarily concerned with measurement of fracture rates, the theoretical framework of fracture kinetics is also examined. Such fundamental understanding provides a rational basis for extrapolation or prediction and thus increases the applicability of existing data bases.

Creep fracture processes

An important mode of failure at high temperature is characterized by a general degradation of the microstructure of a material with time until fracture occurs. This process is called creep fracture. We are investigating the nucleation, growth, and linkage of the creep cavities that constitute the physical damage resulting in fracture under these conditions. We are developing hypotheses and performing experiments that elucidate the role and interplay of these processes in the overall failure mechanism.

There are very few techniques that have sufficient resolution to study the nucleation of creep cavities. Being only nanometers in diameter, cavities at the nucleation stage of development can only be seen by high-resolution transmission electron microscopy (TEM). However, it is not practical to make quantitative measurements by TEM because the density of cavities is too low. Small-angle neutron scattering (SANS), however, is sensitive to these small cavities and can probe cubic centimeters of material. For this reason, a program to measure the time evolution of the size distribution of cavities using SANS was undertaken. Preliminary SANS studies have been carried out on 304 stainless steel creep specimens. Work on 99.99 percent copper is under way.

In addition to the nucleation studies, the growth and spatial distribution of creep cavities occurring around notches in 304 stainless steel have been monitored using quantitative microscopy. Here we are seeing the result of both the nucleation and growth of cavities in nonuniform, multiaxial stress fields. We are beginning to quantify the conditions required for localization of the creep degradation.

Microstructural effects on impact fracture

Of considerable interest to many users of a material is the effect of small variations in the microstructure of that material on its mechanical properties. In conjunction with a NAVSEA program to develop an alternate for the HY-80 steel used in ships and submarines, we are investigating the effect of microstructural variations on the impact fracture properties of a precipitation-hardening HSLA steel. Variations in precipitate distribution have been induced in this alloy by different austenitizing and thermal-aging treatments. We have characterized the microstructure using optical microscopy, TEM, and SANS. The sensitivity of the impact properties of the alloy to variations in heat treatment and microstructure was determined.

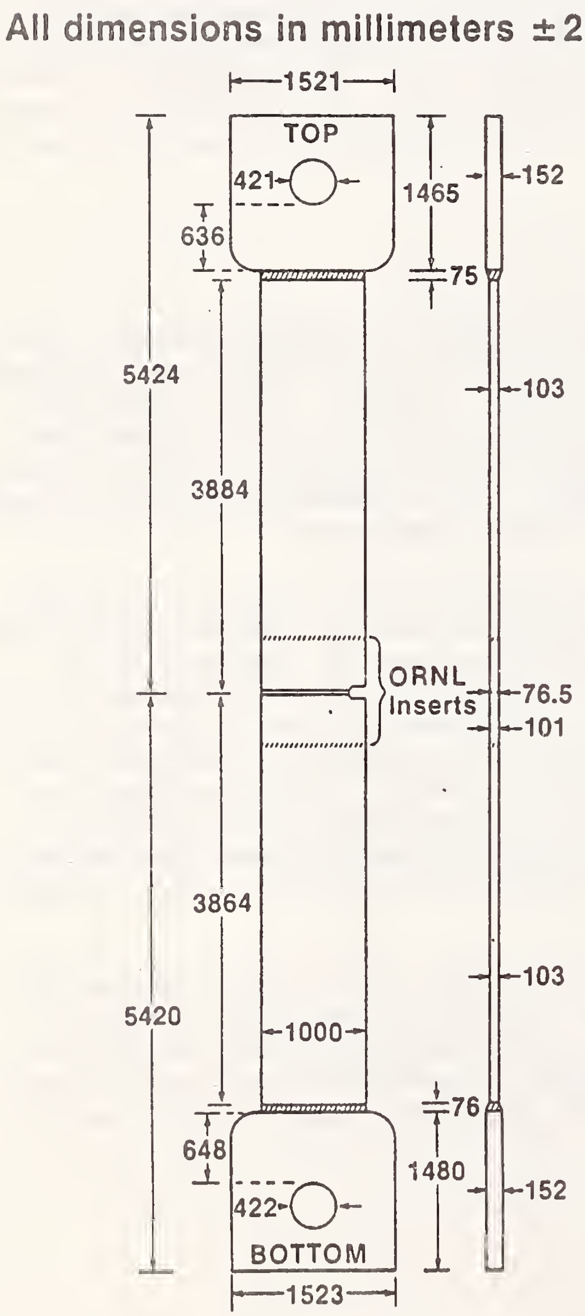

Fig. 1. Specimen for the first wide-plate test.

Dynamic fracture

Crack arrest toughness is the ability of a material to stop a running crack; it occurs when the dynamic stress/strain fields at the tip of a running crack are insufficient to cause the fracture to continue. If material of sufficient crack arrest toughness can be placed properly in a structure, then fractures that initiate in brittle zones can be stopped before complete rupture of the structure occurs. Crack arrest considerations are important in assessing the margin of safety in a structure.

To ensure the reliability of pressurized nuclear reactors, the division has undertaken a study of dynamic crack growth and arrest in wide plates of nuclear pressure vessel steel. The study will provide the basic data required by the nuclear industry to predict pressure vessel behavior during the thermal shock that would accompany an emergency reactor shutdown. We anticipate that the results will have broad implications and be useful in failure avoidance in many commercial and military applications.

The first wide-plate crack-arrest test was performed at the National Bureau of Standards on September 28, 1984. This was the first of six planned tests that use specimens from plate 13A of A533, Gr B, Cl 1 steel. These tests were planned to provide crack-arrest data at temperatures up to or above that corresponding to the onset of the Charpy upper shelf, as well as providing information on the dynamic fracture process for use in evaluating improved fracture analysis methods. The tests use single-edge notch plate specimens that are heated on one edge and cooled on the other to give a linear temperature gradient along the crack propagation plane. Upon initiating the crack in cleavage, arrest is intended to occur in the higher-temperature ductile region of the specimen.

The plates are tested by initiating a rapidly running crack in a single-edge-notch, tensile specimen that is in a temperature gradient. As the crack enters warmer material, it requires progressively more energy to propagate and eventually arrests within the plate. This sequence of events and the associated stresses and strains are monitored by an extensive array of strain gages, timing wires, thermocouples, dynamic amplifiers, and high-speed digital oscilloscopes. The specimen's large dimensions (0.1 m x 1 m x 10 m) are dictated by the speed of sound in the steel, the speed of crack propagation, and the need to achieve plastic constraint. A total of 10 to 12 tests are underway at loads ranging from 1 to 3 million kilograms. These will be the highest-load tensile tests ever performed in the United States.

Oak Ridge National Laboratory provided the specimen illustrated in Fig. 1, which we instrumented with strain gages and thermocouples. In addition, Battelle Columbus Laboratories placed four conducting paint grids along the crack path to measure crack propagation velocity. The specimen was fractured in a thermal gradient that, in the most extreme case, might extend from -101°C to 260°C (-150°F to 500°F) across the 1-m specimen width. To establish this gradient, a heating and cooling system was constructed. An important part of this study was data acquisition from the numerous strain gages, thermocouples, and timing wires that are mounted on the specimen. Battelle Columbus Laboratories was responsible for installing instrumentation to measure crack velocity and acquiring these data. We were responsible for all other data acquisition. Low reactance bridges, wide-range dynamic amplifiers, and high-speed digital oscilloscopes monitored the strain gage response to crack propagation and arrest.

To ensure a meaningful crack run and arrest event, it was necessary to achieve a significant elevation in K above K_{Ic}. The technique chosen was warm prestressing. The specimen was initially loaded to 10 MN (K_{Ia}=117 MPa$\sqrt{m}$) at 70°C to warm prestress the crack tip to prevent crack initiation from occurring at lower loads after the temperature gradient was applied.

A companion crack-arrest study on smaller specimens provided additional data on the behavior of the apparent critical stress intensity factor for crack arrest, K_{Ia}, as a function of temperature. Speculation has centered on "the wall," the apparent tenfold rise of K_{Ia} at 40 to 60°C. Further studies are in progress to clarify the cause of this behavior. The amount of plasticity at the crack tip is believed to play a key role in the cause of the "wall" behavior.

Structure- and Temperature-Dependent Properties
Subtask 4 of Task 12121

R. J. Fields, J. M. Arvidson, R. deWit, R. J. Fields, D. E. Harne, G. E. Hicho, M .B. Kasen, P. T. Purtscher, R. P. Reed, L. C. Smith, L. L. Scull, R. L. Tobler, R. P. Walsh

Essential to the development of new materials or to the improvement of current materials through processing or alloying is understanding the effects of structure and temperature on fracture and deformation characteristics. Phase transformations, grain size, dislocation and point defects, solid-solution alloying, inclusions and precipitates, interface behavior, and particle size and aspect ratios all influence the mechanical performance of structural materials.

Research ranges from studies on austenitic and high-strength, low-alloy steels to rapidly solidified materials. Properties that are measured and modeled include tensile (flow strength, temperature dependence, activation energy and volume), fatigue (low and high cycle), threshold spectrum loading, crack growth rates, fracture toughness (J-integral, CTOD), shear, bend, and impact. Measurement variables include high and low temperatures, irradiation, and strain rate. In the majority of programs there is close collaboration with industry, ensuring immediate assistance in material development.

Interstitial and solid-solution strengthening of austenitic stainless steel

Interstitial strengthening of conventional austenitic Fe-Cr-Ni alloys is achieved by adding nitrogen, and increased alloy formability and nitrogen solubility limits are achieved by adding manganese. The influences of nitrogen and manganese on the temperature dependence of the flow strength, activation energies and volume, martensitic transformations, fracture toughness, and fatigue crack-growth rates from 295 to 4 K are being studied.

AMAX Research and Development Center and Carpenter Technology have provided controlled austenitic steels for our studies of nitrogen, manganese, and molybdenum alloying effects and processing effects on the low-temperature strength and toughness of austenitic steels. A collaborative program of Carpenter Technology, Rockwell International (Rocky Flats Plant), and the Steel Research Center (Colorado School of Mines) has been initiated to study thermal-mechanical processing of high-nitrogen austenitic steels.

The tensile-deformation characteristics and effect of strain rate were studied on relatively pure CDA 102 copper and solid-solution strengthened AISI 310. Tensile strain rate was varied between two orders of magnitude (2×10^{-3}; 2×10^{-5} s^{-1}) at temperatures ranging from 4 to 295 K. Tensile stress-strain and strain-hardening (Θ) curves were determined for these temperatures. The effect of strain-rate changes on tensile flow strength (σ) was measured from strains near 0.002 (yield strength) to over 0.300. The results suggest three regions of plastic deformation of polycrystalline face-centered cubic metals and alloys:

1. For solute-strengthened alloys at low strain, a region of rapidly decreasing strain-hardening rate and rapidly rising strain-rate sensitivity is strongly dependent on temperature and solute content.

2. At low strain for pure metals and at intermediate strains for solute-strengthened alloys, a strain-hardening region where the slope of $\sigma\Theta$ versus σ is constant and strongly dependent on solute content. In this region, the strain-rate sensitivity plotted against σ has a positive or zero slope, dependent also on solute content.

3. At high strain, a region of dynamic recovery in metals and some alloys. Here, the $\sigma\Theta$-versus-σ trend shows an ever-increasing negative slope, and the plot of strain-rate sensitivity versus stress shows an ever-increasing positive slope.

Finally, there is less strain-rate sensitivity at very low temperatures, although specimen adiabatic heating at higher strain rates does result in the lowering of the flow stress.

The tensile strength and fracture toughness at 4 K were studied as a function of nickel (6 to 15 wt.%) and nitrogen (0.09 to 0.28 wt.%) contents for eight austenitic stainless steels. Results indicate that nickel increases the tensile yield strength and decreases the fracture toughness, $K_{Ic}(J)$. Nickel has little significant effect on tensile yield strength but increases the fracture toughness. The temperature dependence of the yield strength, σ_y, follows the relationship $\sigma_y = \sigma_o e^{-AT}$, where σ_o is the yield strength at 0 K and A is the slope of $\ell n\ \sigma_y$ vs. T. The parameter A is proportional to the stacking fault energy. Nickel increases stacking fault energy, austenite stability and the fracture toughness at 4 K of the austenitic alloys (Fig. 2). Lower nickel alloys exhibited brittle facets on fracture surfaces. A new parameter, called the <u>quality index</u>, is presented and defined as the product $\sigma_y \cdot K_{Ic}(J)$. This factor relates to the capacity of the alloy to achieve greater strength or toughness, but not at the expense of the other parameter. Nickel alloying increases the quality factor; nitrogen has little effect.

Thirty-two alloys were included in a study of notch tensile testing as a method of fracture toughness characterization for austenitic stainless steels at 4 K. For the same austenitic stainless steels, tensile and J-integral fracture toughness [$K_{Ic}(J)$] measurements have been conducted. The notch tensile strength (σ_{NTS}) generally increases with yield strength (σ_y), and the σ_{NTS}/σ_y ratios are typically much greater than 1.0. Correlations between σ_{NTS}, $K_{Ic}(J)$, and σ_y were assessed. The best data fit was found between the ratio $\sigma_{NTS}/K_{Ic}(J)$ and the toughness, $K_{Ic}(J)$. Unfortunately, from this relation there is not uniqueness of K_{Ic} from σ_{NTS}. There are three regions in plots of J-integral fracture toughness versus cylindrical bar notch-tensile measurements: (1) linear elastic [σ_{NTS} increases as $K_{Ic}(J)$ increases]; (2) elastic-plastic [σ_{NTS} is essentially independent of $K_{Ic}(J)$]; (3) plastic [σ_{NTS} decreases as $K_{Ic}(J)$ increases]. The elastic-plastic region is associated with a plastic zone that extends completely through the notched cross-sectional area.

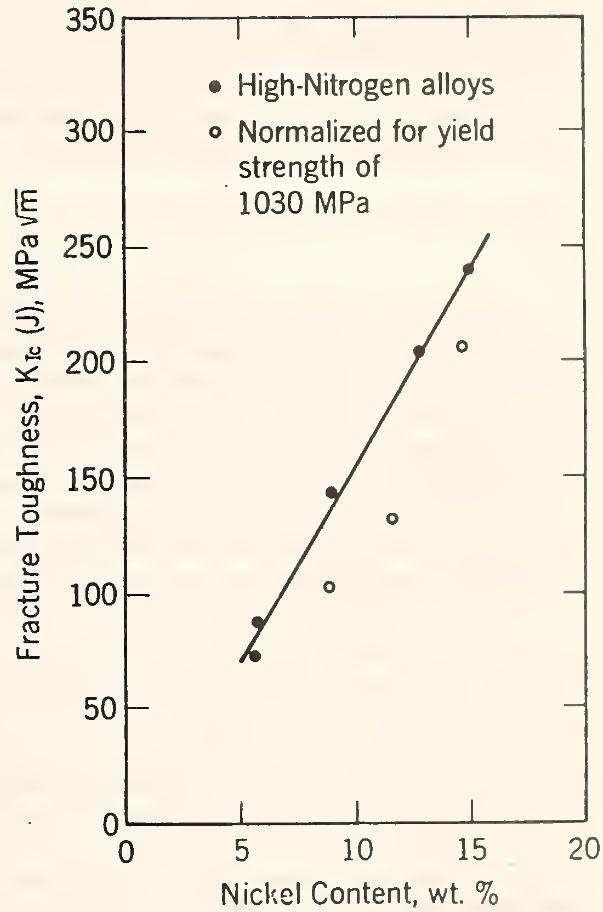

Fig. 2. Fracture toughness at 4 K, estimated from J-integral measurements, versus nickel content.

Microstructural effects on plastic deformation

In conjunction with the investigation of microstructural effects on impact fracture, we are also studying the effect of microstructural variables on the yield stress, the hardness, and the strain hardening and plastic instability behavior of a precipitation-hardened HSLA steel. We induced variation in grain size and precipitate distribution in this alloy by variations in austenitizing and aging treatments. We are presently characterizing the microstructure using optical microscopy, TEM, and SANS. The influence of precipitates and grain size were measured separately and quantitatively. A rare type of fracture, star fracture, was observed in this alloy for certain heat treatments. This type of fracture may limit the applicability of this high-strength steel. The causes of this fracture behavior were determined. Efforts are underway to identify heat treatments or thermomechanical treatments to remedy this behavior. We have measured the plastic properties and correlated them with the microstructure, when possible, using elements of dislocation theory. Most importantly for users of this steel, we have determined how sensitive its deformation behavior is to variations in heat treatment and microstructure. We have completed the work on four heats of steel this year.

Composite Mechanics
Subtask 5 of Task 12121

M. B. Kasen, R. D. Kriz, H. M. Ledbetter, J. M. Arvidson, L. L. Scull, M. W. Austin, S. A. Kim, M. Lei[1]

[1]Guest Worker, Shenyang Institute

The composite mechanics activity addresses three primary areas of research. A substantial effort is directed toward the development and refining of models that will permit accurate prediction of composite material deformation and fracture under a wide variety of conditions. This is particularly important in composite technology where the heterogeneity of the material and the complexity of reinforcement type and distribution precludes the obtaining of such data by experimental means. Primary interest is in understanding damage accumulation mechanisms, factors influencing elastic properties, and parameters influencing residual stress.

Effort is also directed toward understanding the significant parameters influencing mechanical and physical degradation of organic-matrix composites under neutron irradiation at 4 K. These basic data are required in development of functional insulators for superconducting magnets in magnetically confined fusion energy systems. A major effort involves the fabrication and testing of extremely well-characterized research materials.

We also capitalize on our expertise in cryogenic testing of composite and nonmetallic materials by planning and conducting test programs for other agencies, which at the same time contribute to our basic understanding of material performance. This has involved extended-time creep tests and the generation of cryogenic mechanical property data on a specialized silica aerogel foam product used in advanced technology applications.

Finite-element analysis

In considering the mechanics of composite materials, the group focuses on the mechanics of fracture, dynamics, and stress-wave propagation. It studies various damage states by modeling representative boundary-value problems. Because of the complex nature of the boundary-value problems, solutions are obtained by finite-element methods. Influence of thermal-moisture conditions is included in the analysis for studying the fracture process at cryogenic temperatures. Unidirectional, layered, and woven composites have been studied. Emphasis is placed on using the correct set of elastic constants in the solution to the boundary-value problem. Similarly, the influence of variations in elastic properties on acoustic properties has been studied. From these studies a patent was obtained that allows in-situ monitoring of changes in constituent properties of a unidirectional fiber/matrix composite. A possible new technique to monitor dosage of neutron irradiation resulted from similar studies. Optical fibers are used to measure in-situ the crack-arrest mechanism of load transfer from broken fibers to neighboring unbroken fibers. From these experiments we can measure crack-opening displacements between broken fiber ends and local strains in regions of stress concentration.

Experimental results can now be compared with theory predicted by a variety of shear-lag models. Analytical techniques used include: variational methods in predicting composite elastic properties and singularities in stress fields near cracks; perturbation theory to study field singularities; and numerical methods to obtain solutions to complex boundary-value problems. Currently, we use statistical analysis to study the fracture process of laminated composites.

Composite-material property modeling

The composite-material property modeling involves complete quantitative mathematical modeling combined with careful measurements on well-chosen materials. For elastic constants, the modeling involves scattered plane waves from an ensemble of ellipsoidal inclusions. In the measurements we always try to determine the complete physical-property tensor: usually nine independent components in the case of elastic constants, for example. In the modeling, we consider the effects of particle volume fraction, particle shape, particle orientation, particle size, and degree of nonhomogeneity of particle distribution. Our modeling capabilities include particle, fiber, and cloth reinforcements. Currently, we are considering the effects of inclusion-matrix interfaces.

Internal strain

A new activity within the group is the study of internal strain (residual stress) in two-phase materials, especially reinforced composites. In such composites, the elastically stiffer reinforcing phase possesses lower thermal expansivity than the softer matrix phase. Thus, when the two constituents form interfacial bonds at high mixing temperatures and are then cooled to room temperature, thermal stresses arise. These stresses reach enormous magnitudes. In SiC/Al, for example, a temperature change of 50 K produces a

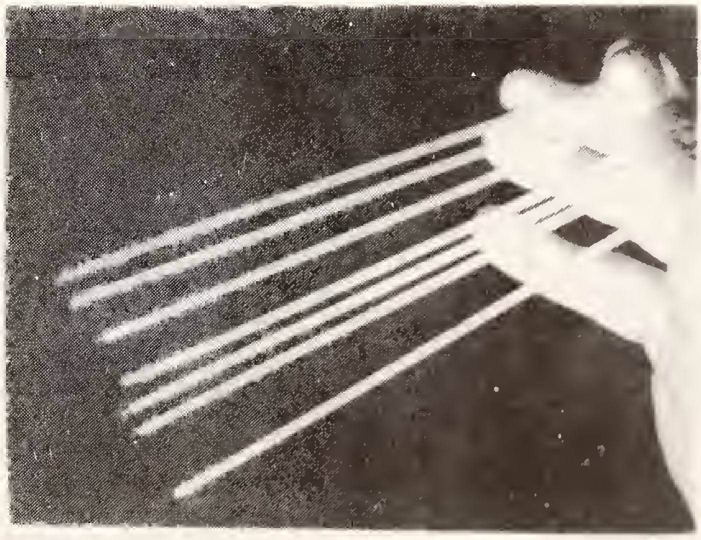

Fig. 3. Specimen rods (3.2-mm diameter, 40-cm long) containing 48 v/o type E glass in an epoxy matrix.

stress exceeding the aluminum-alloy yield strength. Thus, considerable plastic deformation and work hardening occur. Currently, we use two approaches to these studies: x-ray diffraction from both phases and elastic modeling following Bitter and Eshelby. We hope that there will be opportunities to extend the modeling to plastic deformation.

Irradiation effects at low temperatures

Determination of the parameters influencing deterioration in performance of nonmetallic insulators in superconducting magnets subjected to neutron irradiation at 4 K continues to be the goal of a joint program of NBS, LANL, ORNL, and MIT. Primary responsibilities of NBS personnel are to provide highly characterized, fiber-reinforced and unreinforced polymeric test materials, to perform pre- and postirradiation mechanical testing, and to analyze the influence of irradiation on failure modes. We are also taking the initiative in stimulating international cooperation among laboratories conducting similar research.

The experimental program requires screening the interaction of a large number of material variables, including differences in matrix resin and cure state, and differences in fiber type, content, and surface finish. To accomplish this most efficiently, we have developed and refined laboratory techniques for producing the 3.2-mm-diameter rod specimens illustrated in Fig. 3. As illustrated in Fig. 4, the quality of these specimens is extremely high and is representative of the best that has ever been obtained in composite material production. The process has been proven in the production of type E glass reinforced and neat resin specimens representing three types of epoxy resin and a bismaleimide polyimide resin.

We have also developed specialized short-beam shear and torsional shear test methods for evaluating the influence of cryogenic irradiation on degradation of neat resins and of the interface between the glass reinforcement and the polymer matrix. Figure 5 illustrates a typical torsional shear failure at

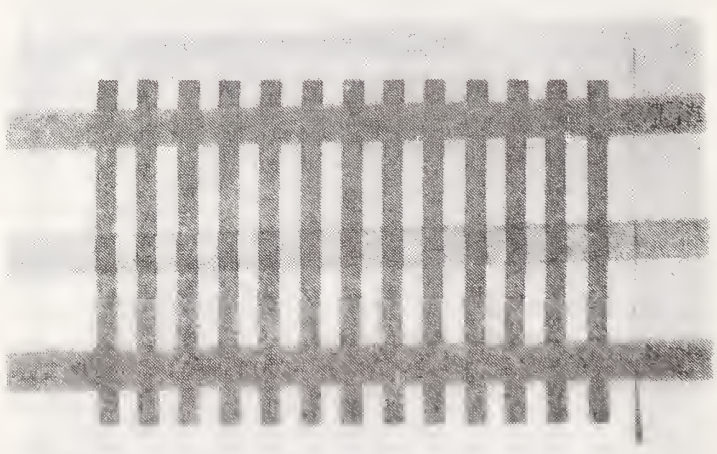

Fig. 4. Transparency of rods containing 48 v/o glass reinforcement illustrates quality obtained. Top to bottom: DGBA/DDS epoxy, DGBA/AMD/POPA epoxy, bismaleimide polyimide.

76 K. This test method is of particular value in studying interfacial integrity because the applied stress is resolved normal to the fiber reinforcement (mode-I interfacial failure) rather than parallel to the fiber (mode II). This is the first time this test mode has been used with composite materials at cryogenic temperatures.

Cooperative work continues with laboratories in Japan and England. A group headed by T. Okada at Osaka University has developed procedures for producing the same specimen configuration reinforced with glass, graphite, silicon carbide, and alumina fibers. They are evaluating the suitability of using three- and four-point flexural strength test methods as material performance criteria. D. Evans of the Rutherford Appleton Laboratories in England has produced and evaluated similar specimens in flexural strength and has contributed expertise to the selection of appropriate resin systems for radiation resistance.

Insulators for superconducting supercollider magnets

We have provided consultation to Fermilab on the selection of materials for thermal standoffs required to support the many superconducting magnets that will be required in construction of the proposed superconductive supercollider (SSC) high-energy physics proton accelerator. We reviewed existing data on cryogenic mechanical and physical properties of existing candidate materials and suggested values to be used for preliminary design purposes. We provided a separate report reviewing the factors to be considered in selecting insulators for maximum dimensional stability and for maximum resistance to ionizing radiation.

We cooperated with the Lawrence Berkeley Laboratory SSC design group by performing a six-week experiment to provide initial data on the thermally activated creep of a uniaxial glass-fiber-reinforced, pultruded rod that they are considering as a thermal standoff member.

Fig. 5. Torsional tests of uniaxially reinforced rod specimens at 76 K typically produce 7 to 10 longitudinal cracks around the specimen circumference (upper specimen). A very brittle matrix can produce a more catastrophic failure within the gage length (lower specimen).

Silica aerogel

Specimens of silica aerogel were tested in compression at 295, 76, and 20 K in a helium gas environment. The properties determined were Young's modulus, the proportional limit, and yield strength. Compressive stress-versus-strain curves are shown in Fig. 6.

A test apparatus was developed specifically to determine the compressive properties of low strength materials, such as silica aerogel. It uses a frictionless, concentric, overlapping-cylinder, capacitance extensometer and has the capability for variable temperature tests at any temperature from 1.8 to 295 K.

Results from the silica aerogel compression tests indicate that at low temperatures the material is not only stronger, but tougher. During 295-K compression tests, the samples fracture and, in some cases, crumbled. After 76- or 20-K compression tests, the specimen remained intact.

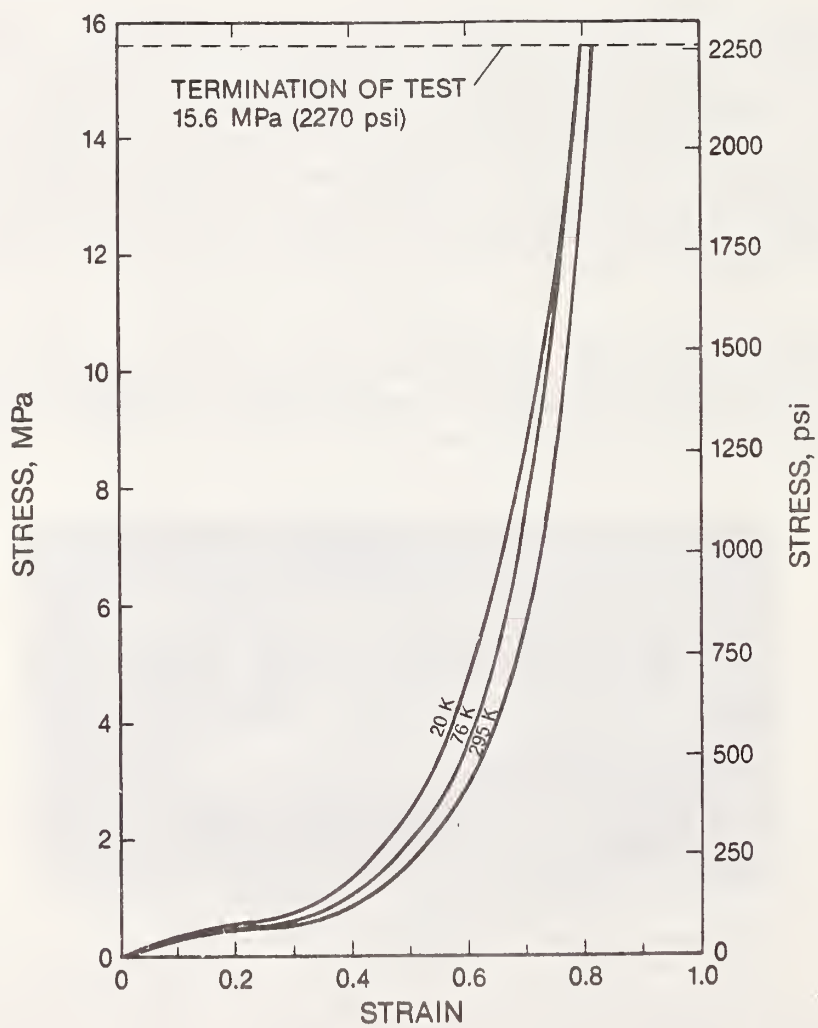

Fig. 6. Stress versus strain behavior for silica aerogel at 20, 76, and 295 K (nominal density = 0.1 g/cm^3).

Material Performance
Subtask 6 of Task 12121

H. I. McHenry, R. J. Fields, L. C. Smith, C. Brady, D. Harne, S. Low, G. E. Hicho, T. R. Shives, N. J. Simon, B. W. Christ, R. P. Reed

Assessment of the behavior of materials while in service provides valuable insight regarding the ability of models and laboratory tests to predict performance. Division activities, such as failure analyses for other government agencies, compilation and review of material performance for specific technologies, and workshops and conferences, provide the opportunity to learn about material problems in service.

Industrial savings in fracture control costs

Economic studies by our division on national costs of fracture of structural materials estimate that about thirty-five billion (1982) dollars might be saved annually through improved technology transfer. A substantial portion of the potential savings could be realized in the automotive sector of the economy--approximately three billion (1982) dollars annually. A joint project with the Ford Motor Company under the auspices of the Department of Commerce Science and Technology Fellowship Program intends to develop a methodology for realizing these potential savings. B. W. Christ of the Fracture and Deformation Division, Boulder Laboratories is spending one year on this study at the Ford Research and Engineering Center, Dearborn, Michigan. The study will review structural designs and manufacturing processes prescribed by existing codes and standards and will determine how technology transfer can lead to manufacturing cost reductions through modifications of design, materials selection, and manufacturing processes. Another objective will be to estimate the initial capital investment required to realize the estimated potential savings. This capital investment is expected to appear in the form of costs for data-base development in support of revised and updated codes and standards, improved materials that have less mechanical-property variability, advanced inspection systems, and automated manufacturing equipment. This project dovetails with activities in the DOC Office of Productivity and Technology Innovation, the NBS Offices of Standard Reference Materials/Standard Reference Data, and the NBS Automated Manufacturing Research Facility.

Failure avoidance services

Failure avoidance services to other government agencies and other divisions within NBS include diagnostic failure analysis, mechanical properties testing, metallographic analysis, and metallurgical consultation. The results of this work have been used to assist in the development of safety regulations, in the selection of materials to improve the reliability of components and structures, and in the development of improved test methods and standards. In many cases, diagnostic failure analysis of components has led to the identification of needed research in materials characterization, and this research is now part of the ongoing programs described in this report. During the present year, several reports of specific projects in failure analysis and failure avoidance were completed. Projects were completed for the National Transportation Safety Board, the Federal Railroad Administration, and the Potomac Electric Power Company. Continuing work includes a failure avoidance study on a 41-mm (16-in) diameter natural gas transmission pipeline for the Montana Public Service Commission and a failure analysis investigation on a ruptured pressure vessel in an oil refinery for OSHA, United States Department of Labor.

Continuing work for the Federal Railroad Administration involves identification of the causes of failure in railway tank cars and wheels. For tank cars, we are working on fracture-safe design and improved materials to resist fracture in the event of tank car accidents. The extreme hazard resulting from frequent accidents involving tank cars containing hazardous materials is a national problem of growing significance. Results of our work on tank-car materials have assisted in the development of specifications for a new tank car that will significantly reduce the frequency of major tank car accidents. For railroad wheels, current efforts are focused on analyses of selected wheels that have failed in service and the residual stress of wheels in service.

We have completed a program with the FAA to determine the failure modes of copper conductors used in airport lighting and other instrumentation. Under extreme conditions, aircraft collide with breakaway lighting support structures. The copper conductors do not break easily and cause damage to aircraft and personnel.

Numerous examples of failures from power generating facilities have been examined. The failures covered all aspects of the industry from generator rotors and water pumps to steam heaters and superheater tubes.

Mechanical failures prevention group

The dissemination of information to assist in failure avoidance was continued by the NBS sponsorship of a meeting of the Mechanical Failures Prevention Group, which was organized by the Fracture and Deformation Division. A meeting with the theme "Use of New Technology to Improve Mechanical Readiness, Reliability, and Maintainability" was held in Gaithersburg on April 16-18, 1985.

Development of standard reference material

Under the sponsorship of the NBS Office of Standard Reference Materials, survey and developmental work has begun on SRMs by improving the reliability of quality control measurements, which would benefit the metals industry in general and the steel industry in particular. Initially, the hardness of commercially available standard test blocks for four Rockwell hardness scales will be measured and compared to ascertain whether there is a need to develop specific standard test blocks. As an adjunct to this study, diamond indentors used for indentation hardness will be studied to determine why apparent inconsistencies exist.

Material properties handbook

The Materials Handbook for Fusion Energy Systems (MHFES) is being developed to provide an authoritative common source of material properties for the fusion energy community to use in concept evaluation, design, safety analysis, and performance prediction and verification of fusion energy systems. This single source for properties is essential to ensure a common basis for comparing the eventual performance and economics of the various fusion systems currently under study, in operation, or under construction.

Handbook pages have been provided to the MHFES covering low-temperature properties of structural alloys for the superconducting magnets used for plasma confinement in fusion energy devices. Three nitrogen-strengthened austenitic stainless steels that are the most promising near-term candidates for structural use in superconducting magnets were chosen for initial coverage, based upon previous use at 4 K, weldability, and cost and availability: AISI 316 (including 316N and 316LN), Fe-21Cr-6Ni-9Mn, and AISI 304N, LN, HN, LHN. Preliminary work for preparation of handbook pages on weldments and aluminum alloys 6061 and 5083 was completed in FY 85, and pages covering the mechanical and physical properties of high-nitrogen 304 alloys were provided to users in draft form.

Data from all sources are carefully evaluated. When appropriate, models are developed for analytical characterization of property behavior as a function of temperature, test parameters, or metallurgical variables. Both mechanical and physical properties are included.

A handbook page showing the analysis of yield strength of 316 is reproduced in Fig. 7. For cryogenic design purposes, recommended values would be two standard deviations below the regression curve. A second handbook page (Fig. 8) is an example of equations developed to express the dependence of yield strength of AISI 304 stainless steels upon interstitial nitrogen and carbon content. Another example of information contained in the handbook is a statistical analysis of variation in 4-K yield strength from AISI 304LN plate furnished by one supplier (see Fig. 9). The unexpectedly large range of values is critically important to designers of large cryogenic structures, such as superconducting magnets.

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316 - 13s

SUPPORTING DOCUMENTATION

STRUCTURAL MATERIALS FOR SUPERCONDUCTING MAGNETS

MATERIAL	PROPERTY
AISI 316 STAINLESS STEEL (ANNEALED)	TENSILE YIELD STRENGTH, AVERAGE

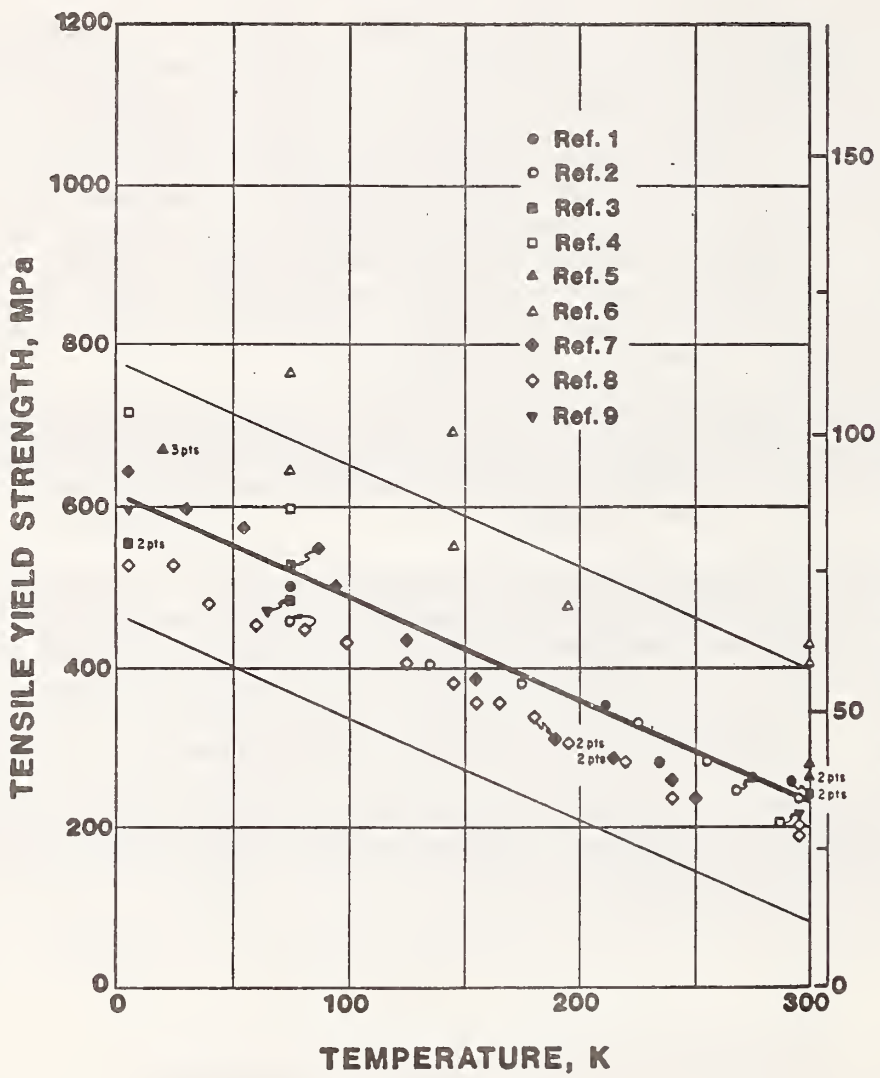

Figure 1. The data shown were used to prepare the average value curve for the tensile yield strength of annealed AISI 316 stainless steel.

Fig. 7. Sample page from Materials Handbook for Fusion Energy Systems, showing graphical presentation of collected data.

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304 - 23

STRUCTURAL MATERIALS FOR SUPERCONDUCTING MAGNETS

MATERIAL AISI 304 (N, LN, HN, LHN) STAINLESS STEEL (ANNEALED)	PROPERTY TENSILE YIELD STRENGTH VS. N, C

Equations predicting tensile yield strength for annealed, high nitrogen 304 plate as a function of nitrogen and carbon content are:

4 K: YIELD STRENGTH (MPa) = 221 + 3613 [N] + 2028 [C]

77 K: YIELD STRENGTH (MPa) = 265 + 2378 [N] + 1625 [C]

293 - 300 K: YIELD STRENGTH (MPa) = 228 + 403 [N] + 508 [C]

where [N] and [C] are in wt.%, and the standard deviations are 62 MPa, 52 MPa, and 24 MPa, respectively. These equations were obtained by fitting 50, 40, and 166 data points at 4, 77, and 293-300 K to an expression linear in [N] and [C]. Other powers of [N] and [C] in similar expressions were also fitted to the data but this did not decrease the standard deviation significantly. The range of nitrogen and carbon content in the set of measurements to which the equations were fitted was: 0.09 wt.% $\leq$ [N] $\leq$ 0.26 wt.%; 0.01 wt.% $\leq$ [C] $\leq$ 0.09 wt.%.

Pages 2 4-2 7 show the predicted tensile yield strength as a function of nitrogen wt.% for fixed carbon wt.% at 4, 77, and 293-300 K, based upon the above three equations.

The above equations are presented only for purposes of alloy design, not for allowable design stress determinations.

Fig. 8. Sample handbook page, showing equations developed from handbook data.

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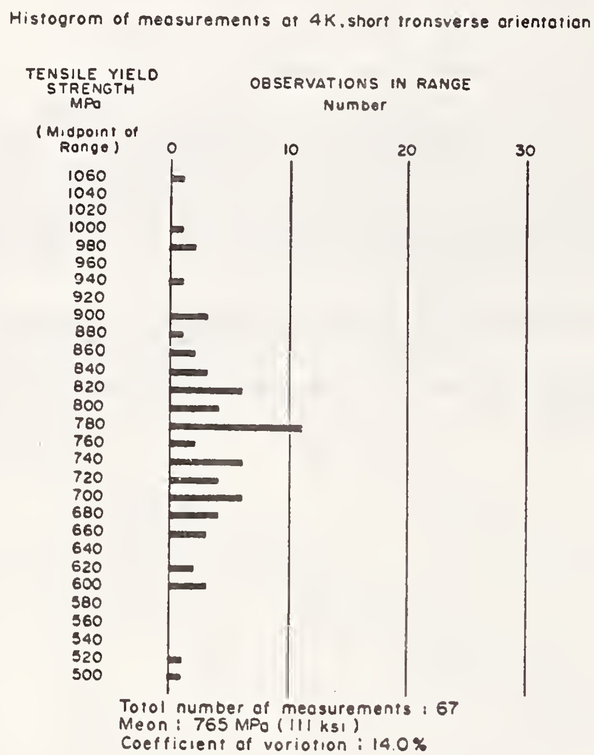
STRUCTURAL MATERIALS FOR SUPERCONDUCTING MAGNETS

MATERIAL AISI 304 (N, LN, HN, LHN) STAINLESS STEEL (ANNEALED)	PROPERTY TENSILE YIELD STRENGTH



These measurements of tensile properties at 4 K were obtained on AISI 304LN production heats from one supplier. For this specimen orientation, nitrogen content ranged from 0.140 to 0.162 wt.% with a mean of 0.150 wt.%; carbon content ranged from 0.014 to 0.029 wt.% with a mean of 0.023 wt.%. Further information on composition, processing, and other characterization parameters is given in the Supporting Documentation Pages.

Fig. 9. Sample handbook page, showing a statistical analysis of variation in a material property.

RECENT PUBLICATIONS

Anderson, T. L.; McHenry, H. I.; Dawes, M. G. Elastic-plastic fracture toughness tests with single edge notch bend specimens, in Elastic-Plastic Fracture Test Methods: The Users' Experience. Wessel, E. T.; Loss, F. J., eds. Philadelphia: Amer. Soc. Test. Mater. STP 856; 1985. 210-229.

Blau, P. J.; Shives, T. R. Micro-indentation hardness testing; applications and interpretation of data, in ASTM Standardization News, vol. 13, no. 1. Philadelphia: Amer. Soc. Test. Mater.; 1985 January.

Carpenter, W. C.; Read, D. T. Comments on the evaluation of the J integral. Int. J. Fract. 26: R71-R74; 1984.

Cheng, Y. W. The fatigue crack growth of a ship steel in saltwater under spectrum loading. Int. J. Fatigue 7: 95-100; 1985.

Cheng, Y. W.; King, R. B.; Read, D. T.; McHenry, H. I. Post yield crack-opening displacement of surface cracks in steel weldments. Sanford, R. J., ed. Fracture Mechanics: Fifteenth Symposium; 1982 July 7-9; College Park, Maryland. Philadelphia: Amer. Soc. Test. Mater. STP 833; 1984. 666-681.

Cheng, Y. W.; Purtscher, P.; Li, P.-N. Fatigue crack growth of duplex stainless steel castings at 4 K. J. Mater. Eng. Technol. 107: 161-165; 1985.

Cheng, Y. W.; Read, D. T. An automated fatigue crack growth rate test system. Cullen, W., ed. Proceedings, Symposium on Automated Test Methods for Fracture and Fatigue Crack Growth; 1983 November 7-8; Pittsburgh, Pennsylvania. Philadelphia: Amer. Soc. Test. Mater. STP 877. Forthcoming.

Cheng, Y. W.; Tobler, R. L. Midrange fatigue crack growth behavior and data correlations for structural alloys at room and cryogenic temperatures, in Fatigue at Low Temperatures. Stephens, R. I., ed. Philadelphia: Amer. Soc. Test. Mater. STP 857; 1985. 3-30.

Clark, A. V. On the use of acoustic birefringence to determine components of plane stress. Ultrasonics 23(1): 21-30; 1985.

Clark, A. V.; Mignogna, R. B. The use of off-axis SH-waves to map out three dimensional stresses in orthotropic plates. Thompson, D. O.; Chimenti, D. E., eds. Proceedings, Review of Progress in Quantitative Nondestructive Evaluation; 1984 August 8-13; San Diego, California. New York: Plenum Press; 1985. 1095-1107.

Clark, A. V.; Mignogna, R. B. The use of off-axis SH-waves to map out three dimensional stresses in orthotropic plates. Ultrasonics 22(5): 205-214; 1984.

Clark, A. V.; Moulder, J. C. Absolute ultrasonic determination of stresses in aluminum alloys. Thompson, D. O.; Chimenti, D. E., eds. Proceedings, Review of Progress in Quantitative Nondestructive Evaluation; 1985 June 23-28; Williamsburg, Virginia. New York: Plenum Press. Forthcoming.

Clark, A. V.; Moulder, J. C. Residual stress determination in aluminum using electromagnetic acoustic transducers. Ultrasonics. Forthcoming.

Clark, A. V.; Moulder, J. C. Ultrasonic determination of principal-stress differences for a slightly anisotropic residual stress specimen. Proceedings, Fifteenth Symposium on Nondestructive Evaluation; 1985 April 23-25; San Antonio, Texas. Nondestructive Testing Information and Analysis Center. Forthcoming.

Clark, A. V.; Moulder, J. C.; Trevisan, R. E.; Siewert, T. A.; Mignogna, R. B. Ultrasonic techniques for residual stress measurement in thin welded aluminum alloy plates. Thompson, D. O.; Cheimenti, D. E., eds. Proceedings, Review of Progress in Quantitative Nondestructive Evaluation; 1985 June 23-28; Williamsburg, Virginia. New York: Plenum Press. Forthcoming.

Datta, S. K.; Ledbetter, H. M. Interface effects on wave speeds and attenuation in composites, in the Role of Surfaces and Interfaces in Material Damping. Metals Park, Ohio: Amer. Soc. Met. Forthcoming.

Datta, S. K.; Ledbetter, H. M. Multiple scattering of elastic waves and effective properties in materials containing inclusions, in Wave Propagation in Inhomogeneous Media, AMD vol. 62. New York: Amer. Soc. Mech. Eng.; 1984. 123-129.

Datta, S. K.; Ledbetter, H. M. Waves, microstructures, and effective-medium approximation. Aifantis, E. C.; Hirth, J. P., eds. Proceedings, International Symposium on Mechanics of Dislocations; 1983 August 28-31; Houghton, Michigan. Metals Park, Ohio. Amer. Soc. Met.; 1984. 213-223.

Datta, T.; Thornberry, D.; Jones, E. R.; Ledbetter, H. M. A novel double-peaked spin-glass susceptibility-temperature response in the ternary alloy $Fe_{69}Mn_{26}Cr_5$. Solid State Commun. 52: 515-517; 1984.

DelSanto, P. P.; Clark, A. V.; Rayleigh wave propagation in deformed orthotropic materials. Thompson, D. O.; Chimenti, D. E., eds. Proceedings, Review of Progress in Quantitative Nondestructive Evaluation; 1985 June 23-28; Williamsburg, Virginia. New York: Plenum Press. Forthcoming.

deWit, R. Dislocation concepts applied to material modeling. Aifantis, H. C.; Hirth, J. P., eds. Proceedings, International Symposium on Mechanics of Dislocations; 1983 August 28-31; Houghton, Michigan. Metals Park, Ohio: Amer. Soc. Met.; 1985. 111-126.

deWit, R. Dislocations. Bever, M. B., ed. Encyclopedia of Materials Science and Engineering. Elmsford, New York: Pergamon. Forthcoming.

deWit, R.; Interrante, C. G. Application of an elastic-plastic model to the use of small specimen strength ratio for measuring fracture toughness. Eng. Fract. Mech. 19: 1151-1159; 1984.

Dodds, R. H., Jr.; Read, D. T. Elastic-plastic response of tensile panels containing short center cracks. Int. J. Fract. 28: 39-54; 1985.

Dodds, R. H., Jr.; Read, D. T. Stress intensity factors for cracks in panels with uniformly spaced holes. Eng. Fract. Mech. Forthcoming.

Fields, R. J.; Danko, G. A.; Low, S. R.; deWit, R. Wide plate crack arrest tests: Instrumentation for dynamic strain measurements. ASTM Standardization News. Philadelphia: Amer. Soc. Test. Mater. Forthcoming.

Fields, R. J.; Harne, D. E.; Fields, B. A. Fracture toughness of a steel matrix, titanium carbide composite. Early, J. G.; Shives, T. R.; Smith, J. H.; eds. Proceedings of the 39th Meeting of MFPG: Symposium on Failure Mechanisms in High Performance Materials; 1984 May 1-3; Washington, D.C. Cambridge, England: Cambridge Univ. Press; 1985 August.

Kasen, M. B. Composite materials in cryogenic space Dewars. Hendricks, J. B., Karr, G. R., eds. Proceedings, 1983 Space Helium Dewar conference; 1983 August 24-26; NASA, Marshall Space Flight Center, Huntsville, Alabama. Huntsville, Alabama: University of Alabama; 1984. 171-179.

Kasen, M. B. Handling blunt flaws in a fitness-for-service assessment of pipeline girth weld quality. Proceedings, Third Summer School on Fracture Mechanics: Fracture Mechanics of Weldments; 1984 June 28-29; Andreleovac, Yugoslavia. Belgrade, Yugoslavia: Univ. of Belgrade. Forthcoming.

Kriz, R. D.; Ledbetter, H. M. Elastic representation surfaces of unidirectional graphite/epoxy composites, in Recent Advances in Composites in the United States and Japan, Hoersch, H., ed. Proceedings, Second U.S.-Japan Symposium on Composite Materials; 1983 June 6-8. Hampton, Virginia. Philadelphia: Amer. Soc. Test. Mater. STP 864; 1985. 661-675.

Kriz, R. D.; Ledbetter, H. M. Elastic-wave surfaces in anisotropic media, in Anisotropic Rheology. Huet, C., ed. Proceedings of the Nineteenth Annual Colloquium on Rheology of Anisotropic Materials, 1984 November 28-30; Paris, France. Forthcoming.

Kriz, R. D.; Muster, W. J. Influence of damage on mechanical performance of woven laminates. J. Compos. Technol. Res. 7: 55-58; 1985.

Ledbetter, H. M. Book review: Non-linear Elastic Deformations by R. W. Ogden (Ellis Horwood, Chichester, 1984). Mater. Sci. Eng. Forthcoming.

Ledbetter, H. M. Comment on "The elastic-stiffness coefficients of nickel-iron single crystal alloys at room temperature." J. Appl. Phys. 57: 5069-5070; 1985.

Ledbetter, H. M. Elastic constants and internal friction of reinforced composites. Wert, C. A.; Granato, A. V., eds. Proceedings, Eighth International Conference on Internal Friction and Ultrasonic Attenuation in Solids; 1985 June 2-6; Urbana, Illinois. J. Phys. (Paris). Forthcoming.

Ledbetter, H. M. Low-temperature monocrystal elastic constants of Fe-19Cr-10Ni. J. Phys. Chem. Solids. Forthcoming.

Ledbetter, H. M. Low-temperature variability of stainless steel 304 elastic constants. J. Appl. Phys. Forthcoming.

Ledbetter, H. M. Manganese contributions to the elastic constants of face-centered-cubic Fe-Cr-Ni stainless steels. J. Mater. Sci. 20: 2923-2929; 1985.

Ledbetter, H. M. Monocrystal elastic constants in ultrasonic study of welds. Ultrasonics 23: 9-13; 1985.

Ledbetter, H. M. Monocrystal-polycrystal elastic constants of a stainless steel. Phys. Status Solidi A85: 89-96; 1984.

Ledbetter, H. M. Predicted monocrystal elastic constants of 304-type stainless steel. Physica 128B: 1-4; 1985.

Ledbetter, H. M. Sound velocity as a texture probe: calculations for stainless-steel-316 welds. J. Appl. Phys. Forthcoming.

Ledbetter, H. M.; Austin, M. W. Anomalous low-temperature elastic-constant behavior of 20Cr-16Ni-6Mn. Met. Sci. 18: 539-542; 1984.

Ledbetter, H. M.; Austin, M. W. Effects of carbon and nitrogen on the elastic constants of 304-type stainless steel. Mater. Sci. Eng. 70: 143-149; 1985.

Ledbetter, H. M.; Austin, M. W. Elastic constant versus temperature behavior of three hardened maraging steels. Mater. Sci. Eng. 72: 65-69; 1985.

Ledbetter, H. M.; Austin, M. W. Elastic constants of an Fe-5Cr-26Mn austenitic steel, 76-400 K. J. Appl. Phys. Forthcoming.

Ledbetter, H. M.; Austin, M. W. Texture in stainless-steel welds: An ultrasonic study. J. Mater. Sci. 20: 1720-1726; 1985.

Ledbetter, H. M.; Austin, M. W.; Callanan, J. E. Internal friction and dynamic Young modulus of a bituminous coal, in Physical Methods for Fossil Fuel Characterization. Conference proceedings, Fuel Division of the American Chemical Society; 1985 April; Miami Beach, Florida. Washington, D.C.: American Chemical Society; 1985. 127-133.

Ledbetter, H. M.; Collings, E. W. Elastic-constant anomalies at the Néel transition in Fe-18Cr-3Ni-12Mn. Mater. Sci. Eng. 68: 233-237, 1984-1985.

Ledbetter, H. M.; Datta, S. K. Damping in metal-matrix composites: Measurement and modeling. Rogers, L., ed. Proceedings, Vibration Damping Workshop; 1984 February 27-29; Long Beach, California. Wright Patterson Air Force Base, Ohio: AFWAL-TR-84-3064; 1984.

Ledbetter, H. M.; Datta, S. K. Effective elastic constants of materials with inclusions. Huet, C., ed. Proceedings, Nineteenth Annual Colloquium on Rheology of Anisotropic Materials; 1984 November 28-30; Paris, France. Forthcoming.

Ledbetter, H. M.; Datta, S. K.; Kriz, R. D. Elastic constants of an anisotropic, nonhomogeneous particle-reinforced composite. Acta Metall. 32: 2225-2231; 1984.

Lin, I.-H.; Hirth, J. P. Changes in stress intensity with dislocation emission from a crack. Philos. Mag. 50: L43-L46; 1984.

Liu, T.-S.; Fields, R. J.; Harlow, D. G.; Delph, T. J. Statistical observations of creep cavitation in AISI type 304 stainless steel. Scr. Metall. 19: 299-304; 1985.

McHenry, H. I. Fracture mechanics, in ASTM Standardization News, vol. 13, no. 11. Philadelphia: Amer. Soc. Test. Mater.; 1985 November.

Mignogna, R. B.; Clark, A. V.; Vold, C.; Rath, B. Acoustic stress measurement in aluminum and steel considering differences in texture due to rolled plate thickness, in Proceedings of Ultrasonics International Symposium; 1983 July; Halifax, Nova Scotia. London: Butterworth Scientific. Forthcoming.

Mignogna, R. B.; Clark, A. V.; Vold, C.; Rath, B. Effects of rolled plate thickness on anisotropy, with application to acoustic stress measurements. Ruud, C. O., ed. Proceedings of Symposium on Nondestructive Methods for Materials Properties Determination; 1983 April 6-8; Hershey, Pennsylvania. Forthcoming.

Moulder, J. C.; Gerlitz, J. C.; Auld, B. A.; Riaziat, M.; Jeffries, S.; McFetridge, G. Calibration methods for eddy-current measurement systems. Thompson, D. O.; Chimenti, D. E., eds. Review of Progress in Quantitative Nondestructive Evaluation, vol. 4; 1984 August 8-13; San Diego, California. New York: Plenum Press; 1985. 411-420.

Purtscher, P. T.; Cheng, Y. W.; Li, P. N. Effect of delta ferrite content on stage II fatigue crack growth of CF8M stainless steel castings at 4 K. J. Eng. Mater. Technol. 107: 161-165; 1985.

Purtscher, P. T.; Krauss, G. Fracture toughness and microstructure of a martensitic, high carbon steel, in Fracture: Interactions of Microstructure, Mechanisms and Mechanics. Wells, J. M.; Landes, J. D.; Stolz, R. E., eds. Proceedings, Symposium on Synergism of Microstructure, Mechanisms and Mechanics in Fracture; 1984 February 28-29; Los Angeles, California. New York: Metallurgical Society of AIME; 1985. 179-194.

Reed, R. P.; Schramm, R. E. Fitness-for-service assessment of pipeline girth welds with emphasis on nondestructive inspection. Proceedings, Third Fracture Mechanics Summer School: Fracture Mechanics of Weldments; 1984 June 28-29; Andreleovac, Yugoslavia. Belgrade, Yugoslavia: Univ. of Belgrade. Forthcoming.

Schramm, R. E.; Moulder, J. C. EMAT/synthetic aperture approach to thick-weld inspection. Thompson, D. O.; Chimenti, D. E., eds. Proceedings, Eleventh Annual Review of Progress in Quantitative Nondestructive Evaluation, vol. 4A; 1984 July 8-13; San Diego, California. New York: Plenum Press; 1984. 225-232.

Schramm, R. E.; Siewert, T. A. Weld flaw sizing using back scattered and forward scattered low frequency ultrasound. Proceedings, Eleventh World Conference on Nondestructive Testing; 1985 November 4-8; Las Vegas, Nevada. Columbus, Ohio: American Society for Nondestructive Testing. Forthcoming.

Siewert, T. A. Moisture in welding filler materials. Weld. J. 64: 32-41; 1985.

Sparks, L. L.; Arvidson, J. M. Thermal and mechanical properties of polyurethane foams at cryogenic temperatures. J. Therm. Insul. 8: 198-232; 1985.

Sparks, L. L.; Arvidson, J. M. Thermal and mechanical properties of polyurethane foams at cryogenic temperatures, in Proceedings, Society of the Plastics Industry - 28th Annual Technical/Marketing Conference; 1984 November 5-7; San Antonio, Texas. Lancaster, Pennsylvania: Technomic Publishing Co.; 1985. 273-286.

Thomson, R.; Chuang, T.-J.; Lin, I.-H. The role of surface stress in fracture. Acta Metall. Forthcoming.

Thomson, R.; I.-H. Lin. Fundamentals of fracture, in Hydrogen Degradation of Ferrous Alloys. Oriani, R. A.; Hirth, J. P.; Smialowski, M., eds. Park Ridge, New Jersey: Noyes Publications; 1985. 454-511.

Tobler, R. L.; Carpenter, W. L. A numerical and experimental verification of compliance functions for compact specimens. Eng. Fract. Mech. 21(3): 547-556; 1985.

Tobler, R. L.; Cheng, Y. W. Midrange fatigue crack growth data correlations for structural alloys at room and cryogenic temperatures. Proceedings, ASTM symposium on Low-Temperature Fatigue; 1983 May 10; Louisville, Kentucky. Philadelphia: Amer. Soc. Test. Mater. STP 857; 1985. 3-30.

Tobler, R. L.; Reed, R. P. Interstitial carbon and nitrogen effects on the cryogenic fatigue crack growth of AISI 304 type stainless steels. ASTM J. Test. Eval. 12: 364-370; 1984 November.

Tobler, R. L.; Shepic, J. Design and performance of a ring-shaped clip gage for fracture mechanics testing. ASTM J. Test. Eval. 13(4): 299-302; 1985.

Tobler, R. L.; Trevisan, R. E.; Reed, R. P. Tensile and fracture properties of an Fe-14Mn-8Ni-1Mo-0.7C fully austenitic weld metal at 4 K. Cryogenics. Forthcoming.

Wnuk, M. P.; Kriz, R. D. Continuous damage mechanics model of fracture in laminated composites. Int. J. Fract. 28: 121-138; 1985.

TECHNICAL/PROFESSIONAL COMMITTEES: LEADERSHIP ACTIVITIES

American Society for Metals (ASM)

Joining Division - Government Liaison - T. A. Siewert

American Society of Mechanical Engineers (ASME)

Joint Applied Mechanics Division (AMD) and Materials Division (MD): Committee on Constitutive Equations - R. deWit

American Society for Testing and Materials (ASTM)

D30	High Modulus Fibers and Their Composites Committee - R. D. Kriz
E9	Fatigue Committee - R. deWit
E9.03	Fatigue of Composites Subcommittee - M. B. Kasen
E24	Fracture Testing Committee - B. W. Christ, R. deWit, G. E. Hicho, S. R. Low, D. T. Read, R. P. Reed, R. L. Tobler
E24.01	Fracture Mechanics Test Methods Subcommittee - R. deWit, G. E. Hicho
E24.02	Fractography and Associated Microstructures Subcommittee - R. deWit
	Coordination of symposium pertaining to the correlation of fracture surface appearance with J-integral test results - G. E. Hicho
E24.03	Alternative Fracture Test Methods Subcommittee - R. deWit
E24.04	Subcritical Crack Growth Subcommittee - R. deWit, R. L. Tobler
E24.05	Terminology Subcommittee - R. deWit
E24.06	Fracture Mechanics Applications Subcommittee - R. deWit, D. T. Read
E24.06.04	Weld Testing - H. I. McHenry
E24.07	Fracture Toughness of Brittle Nonmetallic Materials Subcommittee - R. deWit
E24.08	Elastic-Plastic and Fully Plastic Fracture Mechanics Subcommittee - R. deWit
E28.06	Mechanical Testing - Hardness - R. J. Fields, T. R. Shives
E28.06.07	Hardness Test Block Intercomparison Task Group - R. J. Fields; Chairman, T. R. Shives; Cochairman
E38	Resource Recovery - T. R. Shives
	Mechanical Testing Committee - B. W. Christ
	Planning committee for 18th National Symposium on Fracture Mechanics - H. I. McHenry, D. T. Read, R. P. Reed

American Welding Society (AWS)

C5E SAW Recommended Practices Subcommittee - T. A. Siewert
Technical Papers Committee - T. A. Siewert

American Welding Society (continued)

R. D. Thomas Award Committee - T. A. Siewert
1985 Conference on Fitness for Service of Welded Structures Organizing Committee - M. B. Kasen

American Welding Institute (AWI)

On-line Welding Data Base Committee - T. A. Siewert, B. W. Christ, R. P. Reed

International Cryogenic Materials Conference (ICMC)

Board of Directors - R. P. Reed
1985 Conference Program Committee - M. B. Kasen
Finance Officer - R. P. Reed

International Institute of Welding (IIW)

Commission II Arc Welding - T. A. Siewert
Commission IX Behavior of Metals Subjected to Welding - T. A. Siewert

Mechanical Failures Prevention Group

Committee Member - S. R. Low
Executive Secretary - T. R. Shives
Editor of Proceedings - T. R. Shives

Metals Properties Council

Materials for Utilization at Cryogenic Temperatures Task Group - M. B. Kasen
Technical Advisory Committee - R. P. Reed

Metallurgical Transactions

Board of Review - H. M. Ledbetter

NBS Boulder Editorial Review Board - H. M. Ledbetter, Chairman; J. C. Moulder

National Electrical Manufacturers' Association (NEMA)

Federal and Military Specifications Committee - T. A. Siewert

Pressure Vessel Research Committee

Hydrogen Embrittlement Committee - G. E. Hicho

U.S. Department of Energy, Office of Fusion Energy

Analysis and Evaluation Task Group - N. J. Simon
Conductor Sheath Advisory Group - R. P. Reed
Joint U.S.-Japanese Exchange Program Advisory Committee - H. I. McHenry, R. P. Reed

Versailles Project on Advanced Materials and Standards (VAMAS) Task Group

Cryogenic Structural Materials Working Group - R. P. Reed
Technical Working Area, Weld Characteristics - H. I. McHenry, Chairman; M. B. Kasen

Welding Journal

Review Board - T. A. Siewert

Welding Research Council (WRC)

Data Base Task Group - T. A. Siewert
High Alloy Committee - T. A. Siewert
Materials and Welding Procedures Subcommittee - T. A. Siewert
Stainless Steel Subcommittee - T. A. Siewert

INDUSTRIAL AND ACADEMIC INTERACTIONS

Industrial

In response to numerous requests from designers in industry, members of our division have supplied data and references on properties of specific materials and advice on material selection, data interpretation, measurement techniques, and welding procedures. We provided handbook data on the cryogenic properties of stainless steel alloys to many industries. Our excellent test facilities are often used by industrial personnel. These small requests accrue to a significant assistance to industry. Major industrial cooperative efforts and research were:

Ford Motor Company: Under the auspices of the U.S. Department of Commerce Science and Technology Fellowship Program, B. W. Christ of our division was appointed a "ComSci Fellow" in the Ford Scientific and Engineering Laboratories from July 1, 1985 until June 30, 1986. He will participate in a cooperative study that will review structural designs and manufacturing processes prescribed by existing codes and standards and determine how technology transfer can lead to manufacturing cost reductions through modifications of design, materials selection, and manufacturing processes. Another objective is to estimate the initial capital investment required to realize the potential savings.

Rocketdyne: We have a major low-temperature test program to measure the mechanical properties of selected titanium alloys. To date, research has concentrated on tensile and notch tensile measurements of Ti-5Al-2.5Sn at 20 K. We measured the low-temperature elastic constants of Ti-Al alloys. We initiated and planned a program of low-cycle fatigue testing of Ti-5Al-2.5Sn alloys at 4 K. Special test fixtures have been built. Results of the tests will show the effects of different thermomechanical processes on the fatigue properties of these alloys, which are the structural material for containers of liquefied hydrogen.

The steel industry was surveyed to establish the feasibility of developing a steel with a 450-MPa (65-ksi) yield strength to replace the steels currently used in hull construction that have yield strengths of 350 MPa (50 ksi). Candidate alloys are C-Mn steels microalloyed with niobium and vanadium to provide the increased strength without reducing fracture toughness or weldability. Test plates of the candidate steels were evaluated by Lukens, Bethlehem, and U.S. Steel; samples were given to NBS and David Taylor Naval Ship Research and Development Center for further evaluation. The results of the cooperative program will be used as the basis for a certification program for a grade designated HSLA65.

Welding Research Council: The Welding Research Council (WRC) and NBS have established a joint program to produce nationally recognized weld procedures. At present, welding contractors are required to test and show proof that their procedures produce welds having the required structural integrity. This redundant contractor-by-contractor and job-by-job testing is costly and time-consuming. These individual tests will no longer be required when weld procedures, conforming to the strictest regulatory requirements, have been approved. The WRC is producing a series of welds that represent the nation's most common production practices. These welds, sectioned according to fabrication code requirements, are sent to NBS. NBS is serving as a nationally known, impartial, testing laboratory capable of meeting the various accuracy and identification requirements. We evaluated the mechanical properties and dimensions of several hundred weld specimens this year. The results of our evaluation are being used to develop the first ten preliminary qualification weld procedures.

American Welding Institute: The division is providing assistance to the American Welding Institute (AWI) during its formative period. This organization has been established to improve the transfer of the latest welding technology into United States industry. This year we assisted AWI by planning and establishing a data base on welding technology, which will include information on welding processes, mechanical properties of weldments, procedure qualification test results, and standardized welding procedure specifications. It will eliminate the present duplication of welding procedure qualification tests between American companies. We have assisted in the development of a format for displaying the procedural information on a computer screen. We are adapting the data base software program developed by The Welding Institute of Great Britain to run on the NBS computer. This program will produce a prototype data base for evaluation and testing.

Industrial/Academic

Steel Research Center: The division is closely collaborating with the Steel Research Center, located at the Colorado School of Mines, and partially supported by the American steel manufacturers. The major joint program is a study of the thermomechanical processing of Fe-22Cr-13Ni-5Mn-0.35N austenitic steel to determine the effects of nitrogen on grain-size and cell-structure control during hot rolling. Rockwell International, Rocky Flats is also participating in this program.

Academic

Guest workers from academic institutions were: S. Berge, Norwegian Institute of Technology; J. F. Cardenas-Garcia, Colorado State University; W. C. Carpenter, University of South Florida; M. Lei, Shenyang Institute; D. Mitraković and B. Petrovski, University of Belgrade; R. E. Trevisan, University of Sao Paulo; and M. A. Urendowski, University of Wisconsin.

Lawrence Berkeley Laboratory: We planned and conducted creep tests on a glass-epoxy strut, which is being considered as a magnet support in a proposed superconducting supercollider high-energy physics accelerator.

D. T. Read is working with R. J. Dodds, Jr. of the University of Kansas and W. C. Carpenter of the University of South Florida to develop a three-dimensional J-integral for fracture analysis of surface flaws and other three-dimensional flaws. A three-dimensional J-integral for homogeneous, isotropic materials has been developed and shown to reduce to the two-dimensional case; it is path independent for the one case that has been numerically analyzed (a standard three-point-bend specimen considered in three dimensions). The procedure used for evaluation of the J-integral in fracture toughness testing was shown to produce approximately the maximum value (through the thickness) of the three-dimensional J-integral. Currently a second type of specimen, one with a surface flaw, is being analyzed.

T. A. Siewert is working with R. E. Trevisan of the University of Sao Paulo to identify the effect of electrode weave procedure on the weld fusion line toughness. Single-edge notch bend toughness values of 180 to 315 MPa$\sqrt{m}$ were measured along the fusion line of the various weave procedures. Little difference in toughness was observed when the procedure was changed from no weave to 10-mm weave, indicating high-quality welds can be produced with a wide range of weave conditions. Tensile testing revealed that the weave procedures producing the greatest penetration into the base material increased the yield strength by 10 percent.

H. M. Ledbetter collaborated with S. K. Datta of the University of Colorado on mathematical modeling of the physical properties of composites. Their studies included modeling of SiC particle-reinforced aluminum, fiber-reinforced epoxy composites, inclusions in steel, and microvoids formed during creep in copper.

Staff of the National Magnet Laboratory at MIT and our division are working together to develop mechanical and electrical properties of high-conductivity copper and copper alloys at temperatures ranging from 4 K to room temperature. Special load-control tensile and creep data have been measured at NBS at low temperatures on a series of copper-base alloys.

Scientists in the NDE group are engaged in experimental studies of eddy current test methods and standards in close cooperation with theoretical studies at Stanford University. The goals of the program are to develop measurement methods, calibration procedures, and standards for quantitative eddy current NDE. The NBS efforts are led by J. C. Moulder; B. A. Auld heads the Stanford group. Recent work has focused on developing calibration methods for eddy current measurement systems so that precise, absolute measurements of flaw signals can be obtained for comparison with theoretical models. Progress in these studies has permitted development of new methods for determining the sizes of surface-breaking flaws from eddy current measurements.

J. F. Cardenas-Garcia, an assistant professor at Colorado State University in Fort Collins, calculated J-integrals from full-field strain data. His work included implementing an iterative method to solve the nonlinear tensor equations that relate stress to strain for strains above yield. After calculating the needed stress and displacement-derivative components from the measured data, he calculated the J-integrals for a variety of paths and verified path independence experimentally for the better quality strain data.

W. C. Carpenter, an associate professor at the University of South Florida, visited NBS-Boulder in the 1983-84 academic year. Our collaboration on the extension of the J-integral to three dimensions continued in 1985, with refinement of the details of the effect of finite-element size on the accuracy of the calculation in the elastic and plastic strain ranges.

ASSOCIATED ACTIVITIES

Invited Talks

Individuals in our division presented a total of twenty-six invited talks on a variety of topics, including fracture processes, welding research, physical properties and behavior of composites, elastic constants, fracture mechanics testing and evaluation, and cryogenic steel development in Japan.

Seminars

During the past fiscal year, seventeen seminars were presented at NBS to Fracture and Deformation Division personnel; in nine of these, members of our division discussed their current research. Topics presented by other speakers included: Measurement of Residual Stresses by X-rays; Ductile Fracture of Piping; Fracture and Carbide Morphology of High-Carbon Steel; Damage Development During Multiaxial Fatigue; and Development of an Fe-30Mn-0.3C-0.1Nb Steel for Cryogenic Service.

Conferences Sponsored

The division hosts and leads a number of workshops and conferences each year. In collaboration with the DOE, we host an annual workshop, "Materials at Low Temperatures." The division actively leads and supports the International Cryogenic Materials Conference; the 1985 conference was held at MIT. We organized the ASTM Eighteenth National Symposium on Fracture Mechanics, a three-day symposium held at the University of Colorado in Boulder. The Mechanical Failures Prevention Group, supported by our division, arranged the conference "Enhancing the Technology Base of Failure Avoidance and Durability Improvements." A joint workshop with the American Welding Institute was held on "The Use of New Technology to Improve Mechanical Readiness, Reliability, and Maintainability." We are cooperating with the U.S. Department of the Interior and Colorado School of Mines in sponsoring an international workshop on "Quality in Underwater Welding of Marine Structures" on November 13 and 14, 1985; it will assess accomplishments and needs and set goals for research in this area.

Special Reports and Books

Two symposium proceedings and one handbook were edited by members of our division. Nineteen special reports were written and published, including a 352-page report to the Department of Energy, a major sponsor of our division's research.

External Recognition

U.S. Patent number 4,499,700, "Systems for Monitoring Changes in Elastic Stiffness in Composite Materials," was awarded to R. D. Kriz on February 19, 1985.

H. M. Ledbetter was invited to be a visiting lecturer at the Institute of Applied Physics, University of Tsukuba from September 1, 1985 until March 1, 1986.

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

This report summarized the technical program of the Fracture and Deformation Division of the Institute for Materials Science and Egnineering, National Bureau of Standards for the fiscal year 1985. The division's two major program areas are: elastic-plastic fracture mechanics and fracture mechanisms and anlaysis. Elastic-plastic fractur mechanics includes contributions from stress analysis, material properties, nondestructive inspection, and welding. Division efforts in fracture physics, time-, structure-, and temperature- dependent properties, composite mechanics, and material performance comprise the second area, fracture mechanisms and analysis. Significant technical programs relating to each of these are presented. Major accomplishments are highlighted, including very successful dynamic crack arrest measurements using 10-m-long specimens, development of the dynamic theory of crack tip-dislocation interactions, and continued development and application of finite-element analysis and scattering theory for prediction of composite porperties.

The research areas of the division's professional staff are indicated with each task and detailed in the following staff list. In addition to publishing eighty papers and twenty-two special reports and books, these highly qualified scientists are also leaders in professional societies, conference organizers, invited speakers, and contributors to collaborative research programs with industries and universities, as documented in the concluding section.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

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