WVT-TN-76007



# REPORT OF SECRETARY OF THE ARMY'S RESEARCH AND STUDY FELLOWSHIP



February 1976

BENET WEAPONS LABORATORY
WATERVLIET ARSENAL
WATERVLIET, N.Y. 12189

## TECHNICAL NOTE

AMCMS No. Secretary of the Army's Research and Study Fellowship Program

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The research fellowship discussed in this report was sponsored by the Secretary of the Army's Research and Study Fellowship program. The research work was conducted in the Structures and Materials Group of the National Engineering Laboratory in East Kilbride, Glasgow, Scotland during the period August 16, 1974 to August 16, 1975. A description of the structure and activities of the National Engineering Laboratory is given in section 3.1 of this report. The research program followed was in the general area of materials engineering research and more specifically in the area of fracture mechanics testing and

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20. analysis of high strength structural materials which are used in armament components. The research program which was included in the fellowship application is summarized here and is related to the research work conducted during the fellowship, see section 2. The specific objective of this report is to summarize the significant technical results of the fellowship, including a description of the projects conducted, an evaluation of workers and organizations in my field which were contacted, and some conclusions based on the fellowship experience which relate to armament concerns at Watervliet Arsenal.

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# REPORT OF SECRETARY OF THE ARMY'S RESEARCH AND STUDY FELLOWSHIP

J. H. Underwood

February 1976

U S ARMY ARMAMENT COMMAND

**BENET WEAPONS LABORATORY**
WATERVLIET ARSENAL
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## TECHNICAL NOTE

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The author takes pleasure in crediting Dr. Les P. Pook of the National Engineering Laboratory for his helpful discussions, suggestions and technical support throughout the research fellowship described here.

## 1. INTRODUCTION AND OBJECTIVE

The research fellowship discussed in this report was sponsored by the Secretary of the Army's Research and Study Fellowship program. The research work was conducted in the Structures and Materials Group of the National Engineering Laboratory in East Kilbride, Glasgow, Scotland during the period August 16, 1974 to August 16, 1975. A description of the structure and activities of the National Engineering Laboratory is given in section 3.1 of this report. The research program followed was in the general area of materials engineering research and more specifically in the area of fracture mechanics testing and analysis of high strength structural materials which are used in armament components. The research program which was included in the fellowship application is summarized here and is related to the research work conducted during the fellowship, see section 2.

The specific objective of this report is to summarize the significant technical results of the fellowship, including a description of the projects conducted, an evaluation of workers and organizations in my field which were contacted, and some conclusions based on the fellowship experience which relate to armament concerns at Watervliet Arsenal.

## 2. RESEARCH WORK CONDUCTED

The research program which was proposed in the application for the fellowship is as follows:

(1) Upon arrival present a series of seminars describing recent Army work and Army problems; request seminars and consultations from NEL staff to describe their work.

(2) Study the stress intensity factor calibration for internally pressurized cylinders containing surface cracks and its relation to fatigue track growth and brittle fracture; write or contribute to a technical report describing results.

(3) Study the effects of various aspects of crack geometry and loading on fracture, including (a) crack angle relative to load direction, i.e. modes I and II loading, (b) combined modes I and III loading, (c) the crack-tip plastic deformation process which accompanies mixed mode loading; write or contribute to a technical report describing results.

(4) Contribute to other fracture mechanics work at NEL, including fracture studies with composite materials and studies of the effect of plastic deformation on fracture of metals.

(5) Attend seminars, symposia, technical meetings, and university courses (if applicable).

Items (2), (3) and (4) above, which relate directly to the proposed research, were all covered by the work conducted during the year. And although all of the sub-items above were not covered, work was conducted in related areas which are of direct concern to Watervliet. The work conducted and its relation to the proposed program are described in the following sections 2.1 and 2.2. Summaries of the relevant technical publications are included in the appendix. Copies of the publications are attached to this report.

2.1 <u>New Research Work</u>

Five new research topics were pursued during the year, three with experimental emphasis and two with analytical emphasis.

2.1.1 J-Integral Test Procedure

A technical paper titled "$J_{Ic}$ Test Results from Two Steels" describes fracture toughness tests of a Ni-Cr-Mo steel very similar to gun steel. The results show that the new J-Integral method can be used to measure the fracture toughness of gun steel in thin sections, such as in small bore cannon, and gun steel with high toughness and the large amount of plastic deformation associated with high toughness. The paper was presented at the Ninth National Symposium on Fracture Mechanics in August 1975 and will appear in the ASTM publication of the symposium papers.

2.1.2 Fatigue Crack Growth in a Residual Stress Field

Fatigue crack propagation tests were conducted using bend specimens of Ni-Cr-Mo steel. The specimens were specially prepared so as to produce residual stresses which could be measured very accurately. The significant result from the tests is that the crack growth rate was lowered in part of the area which contained tensile residual stress. The slower crack growth usually seen in compressive stress areas was also seen in tensile stress areas. This quite unexpected result has direct implications in fatigue life estimates of autofrettaged gun tubes which contain tensile and compressive residual stresses. A joint Army-NEL report is being prepared.

2.1.3 Crack Growth in Glass-Epoxy Composites

Fracture tests in glass-epoxy sheet specimens were conducted. Fracture loads were measured with various slits and holes present. These results can be used to access the damage tolerance of glass-epoxy for use in Army aircraft. Test and analysis methods learned from these tests have been included in the plans for a current research project at Watervliet. No publication of this work is planned at this time.

2.1.4 Analysis of Cylinder Stress Intensity Factors

A technical note titled "Note on Cylinder Stress-Intensity Factors" describes an analysis of some recent British K results for internally pressurized cylinders and a comparison of the results with similar unpublished results by Freese and Bowie of the Army Materials and Mechanics Research Center in Watertown. The note has been published in The International Journal of Pressure Vessels and Piping, July 1975.

2.1.5 Analysis of Cylinder Fracture Tests

A technical note titled "A Comment Related to the Crymble, Goldthorpe and Austin Ring Fracture Tests" describes an analysis of the effect of hydrostatic pressure on the fracture behavior of cylinders. Experimental K results presented by Crymble et al at the Second International Conference on High Pressure Engineering are shown to be significantly affected by hydrostatic pressure. The note will be published in the proceedings of the conference.

2.2 Invited Lectures and Review Papers

Three presentations and associated publications were prepared during the fellowship which were based partly on previous work and partly on new analyses and literature studies during the fellowship.

2.2.1 Ultrasonic Crack Measurement

A technical paper titled "End-on Ultrasonic Crack Measurement in Steel Fracture Toughness Specimens and Thick-Wall Cylinders" was presented at a Welding Institute meeting in December 1974. The paper describes the use of ultrasonics to measure crack growth during fracture toughness tests and fatigue crack growth tests. The most significant aspect of the paper is that it clearly demonstrates the accuracy and repeatability of the Watervliet developed ultrasonic method for fracture mechanics testing. The paper will be included in an upcoming Welding Institute book, The Detection and Measurement of Cracks.

2.2.2 C-Specimen Fracture Toughness Tests

A technical paper titled "Fracture Toughness Measurement and Ultrasonic Crack Measurement in Thick-Wall Cylinder Geometries" was presented at the Second International Conference on High Pressure Engineering. The paper describes the use of the C-shaped specimen for fracture toughness testing of material in cylindrical geometries, the prevalent geometry in pressure vessels. The paper will be published in the proceedings of the conference.

2.2.3 Use of Fracture Toughness in Design

One of the lectures in a fracture mechanics course was written and presented during the fellowship. The lecture, titled "Fracture Toughness-Its Use in Fracture Mechanics Design" describes the various accepted methods for measuring fracture toughness and the use of fracture toughness measurements in fracture mechanics design.

3. DESCRIPTION OF PROFESSIONAL CONTACT

3.1 National Engineering Laboratory

The most extensive technical contact during the year was with the host organization. National Engineering Laboratory is the British Government laboratory responsible for research, development and contract work in engineering, primarily mechanical engineering. As part of the Department of Industry, their general mission is to provide engineering support to British industry. To encourage this support a "repayment" procedure has been established in recent years whereby technical staff from a corporation can directly approach individual staff members or groups at NEL, describe an engineering problem and be advised of the cost of NEL contract work to solve the problem. This repayment process provides a valuable service to industry in areas which require special equipment or expertise. It also produces the added benefit of keeping NEL staff in touch with practical problems. Repayment funding of NEL from British industry is growing, but most of the funding is still from more traditional sources, that is, proposals to "requirement boards" made up of government, industry, and university people.

NEL has a staff of 900 divided into four groups. My contact was almost totally with the Structures and Materials Group, headed by Mr. N. E. Frost. Within that group, most of my work involved the Strength of Components and Fatigue Division, headed by Dr. K. J. March, and more specifically the fracture mechanics section, headed by Dr. L. P. Pook. The most impressive general feature of the structure and workings of NEL, particularly in the above areas with which I had most contact, was the high degree of technical and fiscal responsibility which was delegated to staff members at all organizational levels. As examples; the costs of contract work for industry were often established by working-level staff, and second, the technical plans of division heads seemed to be significantly influenced by ideas from below due to the delegation of technical responsibility.

### 3.2 Attendance and Presentations at Technical Meetings

A listing of the technical meetings attended is given, with presentations indicated and comments added where applicable.

3.2.1 Sept. 25, 1974, East Kilbride, Scotland, NEL Research Seminar, an oral presentation of Army interests and fellowship plans.

3.2.2 Oct. 9, 1974, London, Designing Against Fatigue - Implications of Recent Findings on Complex Situations, seminar sponsored by The Institution of Mechanical Engineers. This particular group has not yet made much use of fracture mechanics in the description of fatigue crack growth.

3.2.3 Nov. 19, 1974, London, Residual Stress Measurement by the Hole Drilling Technique, seminar sponsored by Welwyn Strain Measurement Ltd. Seminar participants from Marchwood Engineering Laboratory of the Central Electricity Generating Board described some high level experimental stress analysis work applied to power generating equipment.

3.2.4 Dec. 4, 1974, London, The Detection and Measurement of Cracks, seminar sponsored by the Welding Institute, presentation of a technical paper, "End-on Ultrasonic Crack Measurements in Steel Fracture Toughness Specimens and Thick-Wall Cylinders" by J. H. Underwood, D. C. Winters and D. P. Kendall.

3.2.5 Mar 19, 1975, East Kilbride, Scotland, Designers Guide to Fracture Mechanics, fracture mechanics course sponsored by NEL, presentation of one of four course lectures titled, "Fracture Toughness-Its Use in Fracture Mechanics Design" by J. H. Underwood. One of the other lecturers, Dr. I. Gray from CEGB in Manchester, showed an excellent understanding of fracture mechanics applied to power plant design.

3.2.6 Apr. 8-11, 1975, Geneva, International Conference on Composite Materials, a rapporteur presented a paper titled "Fatigue Damage in

Notched Glass-Epoxy Sheet" by J. H. Underwood and D. P. Kendall. It was interesting to note that nearly all of the applications of composites described at the conference were from U. S. industry and government, primarily aerospace related.

3.2.7 Apr. 27, 1975, Glasgow, British Society for Strain Measurement, regional meeting at the University of Strathclyde, presentation of a technical talk, "Residual-Stress Measurements Using Surface Displacements Around an Indentation", by J. H. Underwood. This technical society, the BSSM, although small and relatively narrow in scope, involves itself with high level stress analysis work with good application to engineering problems.

3.2.8 July 8-10, 1975, Brighton, England, Second International Conference on High Pressure Engineering, presentation of two technical papers, "Materials and Processes Considerations in the Design of Pressure Vessels" by T. E. Davidson, D. P. Kendall, and B. B. Brown and "Fracture Toughness Measurement and Ultrasonic Crack Measurement in Thick-Wall Cylinder Geometries" by D. P. Kendall, J. H. Underwood, and D. C. Winters. At the conference the work of Queens University of Belfast was outstanding, particularly related to fracture aspects of high pressure.

3.2.9 Aug. 25-27, 1975, Pittsburgh, Ninth National Symposium on Fracture Mechanics, presentation of technical paper titled "$J_{Ic}$ Results from Two Steels" by J. H. Underwood. Although this presentation was after the end of the fellowship, it described the results of one of the fellowship projects.

3.3 Informal Technical Contact

Informal technical contact took place with various persons and organizations during the year. A few comments are offered relative to those of particular interest to the Army.

3.3.1 Apart from the host laboratory, the organization with which I was most impressed was the Central Electricity Generating Board, CEGB. I did not visit any CEGB labs, but I had contact with several persons from various labs. Their general engineering expertise seems high and their knowledge and achievements in my field of fracture is extensive. In my opinion, CEGB would make an excellent host organization for future fellowships.

3.3.2 I visited the Royal Armament Research and Development Establishment, RARDE, and talked with Mr. B. D. Goldthorpe. Their gun tube testing facilities and activities are very similar to those at Watervliet but on a smaller scale. Their work on gun tubes with multiple cracks is directly applicable to Watervliet concerns and should be pursued.

3.3.3 I talked extensively with Dr. B. A. Austin of Queens University at the July 75 meeting listed above. His pressurized ring method for testing cracked cylinders results in considerable time savings. It can apply to certain gun tube test applications and will be pursued where applicable.

3.3.4 The only university with which I had significant contact in my field during the year was Queens University in Belfast. No visit to Queens was made, but contact with faculty members Dr. B. A. Austin and Dr. B. Crossland and with Dr. R. W. E. Shannon formerly at Queens indicated to me that Queens is one of the top universities in the fields of high pressure and fracture.

3.3.5 Discussions with R. W. E. Shannon while at the July 75 meeting and technical correspondence related to fracture of cylinders indicated to me that he is extremely knowledgeable in this field, both from experimental and analytical points of view. He is now at the British Gas Council and is involved with thin-wall cylinder problems.

3.3.6 While in Germany on holiday, I visited the U. S. Army Scientific and Technical Information Team (Europe). and talked with Col. T. C. West, Commander, Maj. R. Mangum and Dr. R. Griffin a former co-worker at Watervliet. I was impressed by their concern for and knowledge of practical, hardware-related problems.

3.3.7 I had only phone and letter contact with the European Research Office in London, due partly to geographical separation but more significantly to the fact that my host lab, NEL, provided all the technical support and cooperation that I could conceivably require during the year.

## 4. TECHNICAL IMPRESSIONS AND EVALUATIONS

Some general technical impressions were formed and some evaluations can be made based on the fellowship experience.

### 4.1 Impressions of the Field of Fracture Mechanics in Britain

It is my impression that the overall level of knowledge, expertise, and achievement in the field of fracture mechanics in Britain is lower than in the U. S. but no lower than expected considering the size of effort in a smaller country. Dividing fracture mechanics into analytical and experimental areas, the analytical area, including such items as calculation of elastic stresses and stress intensity factors for complex cracked geometries, is at a lower level than would be expected. The experimental area, including such items as fracture mechanics test methods and experimental determination of fracture criteria is at a higher level than would be expected. Another broad category of the field of fracture mechanics, and one to which a lot of effort is currently being directed in Britain and elsewhere, is ductile fracture. Due to what is in my opinion an unfortunate overemphasis on the crack-opening-displacement approach to ductile fracture in Britain, the level of achievement in understanding ductile fracture is lower than would be expected.

A hopefully unbiased opinion of some reasons for the high and low levels of achievement is as follows. Good achievement in experimental fracture mechanics areas in Britain is due in part to the higher regard for experimental research work in Britain compared to this country. On occasion in the U. S., experimental work will take a second place to analytical work due only to the use of an experimental approach. I did not encounter this tendency in Britain. Low achievement in British fracture mechanics is in part due to two approaches to their R&D work in this field. The first is the tendency for industry and government organizations to consider R&D results as proprietary information and to thus delay the transmission of results to the technical community. The second is the lack of a professional organization which concentrates in the fracture mechanics area and the resulting lack of coordination in this area.

4.2 Evaluation of the Fellowship Arrangements at NEL

One of the key requirements for a successful fellowship is that the host organization provide a technically stimulating but not restrictive or imposing atmosphere for the guest. And, unlike the technical competence and relevance of the activities of the host organization, which can be assessed during the application and approval procedures, the assessment of the atmosphere is difficult to accomplish before the fellowship begins.

In regard to the research atmosphere at NEL, it certainly matched the good overall reputation of the laboratory. In my experience at NEL, the favorable research atmosphere is due in large measure to the excellent research management of Mr. N. E. Frost, head of Structures and Mechanics Group. The fact that the atmosphere was stimulating is indicated by the amount of work initiated and completed during the fellowship. Indications of the cooperative, restriction-free atmosphere at NEL are the following. While planning my work, technical advice was always offered, but no attempts were made to restrict the work to NEL interests. While conducting the work, NEL provided complete technical support, including the providing of test material, machining, testing assistance, report preparation, printing and shipping, and all correspondence and business travel arrangements. In addition, it was my impression that I often received more complete and faster help and support than the usual standard at NEL.

I am happy to credit the following people for their significant contributions to the success of the fellowship. Mr. N. E. Frost, Dr. Ken Marsh, and Dr. Les Pook are the heads of the group, division and section with which I had most contact. Their enlightened approach to research management in general and my fellowship in particular accounted for the excellent fellowship arrangements I experienced at NEL. Dr. Les Pook, with whom I consulted on a daily basis, was more responsible than any other person at NEL for the success of the fellowship. Finally, the excellent cooperation of all the NEL staff with whom I dealt resulted in significantly more work completed during the year than otherwise would have been possible. It is my sincere belief that the excellent cooperation I experienced at NEL is a direct reflection of the unusually fine character of the people of Scotland.

## 5. CONCLUSIONS AND RECOMMENDATIONS

Three items are discussed here which relate to Army armament concerns at Watervliet. The conclusions and associated recommendations result from the interaction of the fellowship experience with my work at Watervliet.

5.1 Based on my knowledge of the R&D effort at Watervliet and my observations during the fellowship, I believe that improved use of the technical competence available at Watervliet and a concomitant improvement in Watervliet's R&D results could be brought about by increased direct, working-level contact between the users of armament components and the R&D staff. Two key elements of a process for encouraging working-level contact would be associated funding to emphasize its importance and an improved system to bring user concerns to the attention of mid-level R&D staff members. A suggested system is the assignment of a "user" to each principal investigator of R&D projects so that regular person-to-person discussions could take place regarding the Army materiel of interest.

5.2 The use of the J-integral ductile fracture criteria should be included in the design of weapons components at Watervliet. Although this criteria is still being developed, it has become the accepted approach by most of the U. S. fracture mechanics community, and it is quickly replacing the crack-opening-displacement approach in Britain for many applications. The current Watervliet effort to incorporate the J-integral fracture criteria in gun tube design should be accelerated. And J-integral criteria should be considered in the design and failure analysis of major gun tube support components and attachments, such as recoil mechanisms, muzzle brakes, and base plates.

5.3 Three topics of recent fracture mechanics research relate directly to fatigue crack growth in gun tubes, the fracture process of primary concern at Watervliet. First, Goldthorpe in Britain has shown that fatigue cracks in gun tubes grow significantly slower when there are many other cracks present. Second, several investigators have shown that fatigue cracks often do not close completely at zero load and this results in slower growth.

Finally, my work with Pook at NEL shows that the retardation of fatigue crack growth with residual stress present is greater than expected. These three effects should be verified for the conditions of our gun tubes. Then their inclusion where appropriate in the fracture mechanics description of fatigue crack growth will result in more accurate fatigue life predictions for gun tubes.

## 6. APPENDIX

Summaries of technical publications which describe the results of the fellowship are given here.

### 6.1 $J_{Ic}$ TEST RESULTS FROM TWO STEELS

by

J. H. Underwood,* M Sc

(Structures and Materials Group: Strength of Components and Fatigue Div)
National Engineering Laboratory

NEL Report No. 600
Department of Industry

September 1975

Fracture toughness tests were performed with 10 by 20 mm, deeply notched bend specimens of a mild steel and a Ni-Cr-Mo steel. The recently proposed J-integral test method was used to determine critical values of the energy line integral for mode I crack growth, $J_{Ic}$, for both steels. The $J_{Ic}$ results are discussed in relation to criteria for specimen geometry and critical crack growth which have been proposed for a standard $J_{Ic}$ test procedure. The $J_{Ic}$ results from the Ni-Cr-Mo steel are in excellent agreement with the known $K_{Ic}$ value, provided that the elastic deflection corresponding to the uncracked specimen is taken into account.

The $J_{Ic}$ results from both steels are shown to be closely approximated by a one-specimen $J_{Ic}$ test procedure, which is described and suggested for use as a fracture toughness screening test.

An analysis is presented of the error in $J_{Ic}$ determination which arises when the effect of uncracked deflection in bend specimens is ignored. The error can be significant for materials with high yield strength relative to fracture toughness, even for deeply cracked specimens.

*Mr. J. H. Underwood, who is on the staff of the US Army Benet Weapons Laboratory, Watervliet, NY, carried out the work reported here while working at NEL on a Secretary of the United States Army Research and Study Fellowship.

## 6.2 FATIGUE CRACK PROPAGATION THROUGH A MEASURED RESIDUAL STRESS FIELD IN ALLOY STEEL

J. H. Underwood*, L. P. Pook** and J. K. Sharples**
*U. S. Army, Benet Weapons Laboratory, Watervliet, N. Y.
**National Engineering Laboratory, East Kilbride, Glasgow, Scotland

Fatigue crack propagation tests were performed using 5 mm by 30 mm cross section bend specimens of a Ni-Cr-Mo steel. The fatigue crack propagation rate was determined from a group of stress-free specimens by measuring crack length on the specimen surfaces at intervals during cycling. Residual stress was produced in a second group of specimens by using a localized plastic deformation process. Resistance strain gages were first applied near one edge of each specimen along the line of intended crack growth. A series of 1 mm deep plastic indentations was then made along the opposite edge of the specimen using a 25 mm diameter pin. The strain gages provided a direct, accurate measure of the elastic residual stress produced on one side of the specimen due to the local plastic deformation on the opposite side.

The measured crack propagation rate in the specimens with residual stress is compared with the rate in the stress-free specimens. The crack propagation rate is lower, as expected, near the edge of the specimen where the residual stress is compressive. But the propagation rate remains lower even as the crack grows deeper into the specimen where the residual stress is tensile. A simple superposition of stress predicts a higher propagation rate with tensile residual stress. However, the observed lower crack propagation rate is supported by a fracture mechanics analysis which involves a superposition of the applied stress intensity and the effective stress intensity determined from the residual stress distribution in the specimen.

## 6.3 A NOTE ON CYLINDER STRESS-INTENSITY FACTORS

J. H. Underwood*
Structures and Materials Group, National Engineering Laboratory
East Kilbride, Scotland

A comparison is made between Shannon's finite element K results for internally pressurized thick-walled cylinders with one and two radial cracks and Bowie and Freese's mapping-collocation results for the same geometries. The comparison is good except for shallow cracks relative to the cylinder wall thickness. Based on the nature of the two calculation techniques and on the comparison of the results for shallow cracks with the known result in the limit of very shallow cracks, the collocation results appear to be the better representation of K. The difference becomes particularly important when the K results are to be used for predictions of cylinder fatigue lives, since shallow crack growth rates dominate fatigue life.

*Research Fellow, US Army Fellowship from Benet Weapons Laboratory, Watervliet, NY, USA
Int. J. Pres. Ves. & Piping (3)(1975).

## 6.4 A COMMENT RELATED TO THE CRYMBLE, GOLDTHORPE AND AUSTIN RING FRACTURE TESTS

J. H. Underwood, MSc
US Army Benet Weapons Laboratory, Watervliet, NY

The ring fracture test is a useful test for determining the fracture pressure of cylinders with straight cracks, and it is certainly easier to perform than conventional tests. The only problem with the test is that mentioned by the authors, that is the effect on the fracture process of the internal pressure which acts on the end faces of the specimen. During the discussion sessions at the Second International Conference on High Pressure Engineering, Dr. Austin, Dr. Tomkins and Prof. Crossland all expressed concern related to the general problem of the effects of pressure on crack-related fracture. The objective here is to consider one aspect of the pressure effect in the ring fracture tests reported by Crymble, Goldthorpe and Austin and to indicate how this consideration can apply to other pressure vessel fracture problems.

For publication in the proceedings of the Second International Conference on High Pressure Engineering, to be published.

## 6.5 END-ON ULTRASONIC CRACK MEASUREMENTS IN STEEL FRACTURE TOUGHNESS SPECIMENS AND THICK-WALL CYLINDERS

J H Underwood*, MSc, D C Winters, MSc and D P Kendall, MSc
US Army Benet Weapons Laboratory, Watervliet, N. Y.

Fracture toughness tests were conducted with standard compact specimens and with C-shaped specimens of a Ni-Cr-Mo steel. The length of fatigue crack in each specimen and the growth of the crack during testing were measured using an end-on ultrasonic method and were compared with direct measurements on the fracture surface. Fatigue crack growth in a pressurized thick-wall cylinder was measured using ultrasonics and compared with measurements on the fracture surface. The ultrasonic method is described and its utility and limitations are discussed.

*US Army research fellow at National Engineering Laboratory, East Kilbride, Glasgow.

## 6.6 FRACTURE TOUGHNESS MEASUREMENT AND ULTRASONIC CRACK MEASUREMENT IN THICK-WALL CYLINDER GEOMETRIES

D P Kendall, MSc, J H Underwood*, MSc and D C Winters, MSc
US Army Benet Weapons Laboratory, Watervliet, N. Y.

*currently on US Army Fellowship at National Engineering Laboratory, East Kilbride

Fracture toughness tests were performed using 'C' shaped specimens cut from thick-wall cylinder forgings of a Ni-Cr-Mo steel. The measured critical $K_I$ value is essentially constant over the range of specimen sizes and is in good agreement with the known $K_{Ic}$ value for the material. A continuous measurement of the crack length was obtained during the fracture toughness tests using an ultrasonic pulse-echo technique. Based on these ultrasonic crack growth measurements and calculated crack growth values from a compliance analysis and on prior work with 'C' specimens, a $K_{Ic}$ test procedure is recommended for the 'C' specimen.

For publication in the proceedings of the Second International Conference on High Pressure Engineering, to be published.

## 6.7 FRACTURE TOUGHNESS - ITS USE IN FRACTURE MECHANICS DESIGN

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Birniehill Institute, National Engineering Laboratory, East Kilbride, Scotland

### Definitions and Misconceptions

A general definition of fracture toughness, following from the basic concepts of fracture mechanics discussed in the previous paper, is given.

Opening Mode Plane-Strain Fracture Toughness

By far the most important measure of fracture toughness is $K_{Ic}$, the opening mode, plane-strain fracture toughness.

Standard $K_{Ic}$ Test Method

The standard $K_{Ic}$ test procedure is described in detail in the British and American $K_{Ic}$ standards which are listed as further reading. Here, the general procedure will be discussed rather than detail.

Large Scale Yielding Fracture Toughness

Large-scale-yielding fracture involves plastic deformation around the crack which is too extensive to ignore. This general area of fracture mechanics is currently receiving a lot of attention and is changing rapidly.

An Example of Fracture Toughness Measurements Used in Design

An example of $K_{Ic}$ measurements and their use in fracture mechanics design is described to show how some of the topics discussed here can be used in a real situation.