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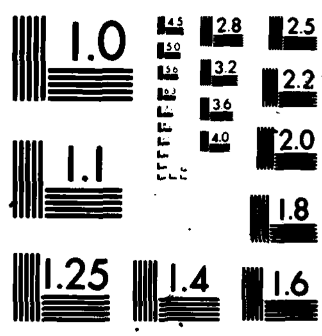

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APPLICATION OF ADVANCED FRACTURE MECHANICS TECHNOLOGY TO ENSURE STRUCTURAL RELIABILITY IN CRITICAL TITANIUM STRUCTURES

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Interim Report for Period 1 June 1980 - 20 November 1980

Prepared for
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Numerous meetings were held with navy personnel in order to identify areas of concern and the experimental data needed for the structural analysis. The mentioned areas cover a broad spectrum regarding loading conditions, material behavior, fabrication procedures, weldments and structural integrity. It is anticipated that recommendations will be made regarding data gathering and/or critical tests for specific needs.

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APPLICATION OF ADVANCED FRACTURE MECHANICS TECHNOLOGY TO ENSURE STRUCTURAL RELIABILITY IN CRITICAL TITANIUM STRUCTURES

H. A. Ernst, J. D. Landes and E. T. Wessel
Structural Behavior of Materials Department

ABSTRACT

The overall objective of this program is to assist the Navy in developing and applying advanced fracture mechanics technology to ensure structural integrity in critical applications of titanium alloys. Numerous meetings were held with Navy personnel in order to identify areas of concern and the experimental data needed for the structural analysis. The mentioned areas cover a broad spectrum regarding loading conditions, material behavior, fabrication procedures, weldments and structural integrity. It is anticipated that recommendation will be made regarding data gathering and/or critical tests for specific needs.

1. INTRODUCTION

The assurance of safe and reliable structural performance of critical components, structures, and equipment subjected to adverse loading conditions has always been a matter of vital concern to both the U.S. Navy and the Westinghouse Electric Corporation. The capability to conduct appropriate structural integrity analyses takes on an added importance when new equipment, designs, materials, inspections and fabrication procedures are concerned.

In these situations there is little or no service experience to rely upon; hence, a thorough structural integrity analysis, incorporating all of the interacting factors must be included as a major element in the overall plan. Such analyses should take advantage of the most advanced technology areas that are applicable to the situation of concern; in this case modern fracture mechanics technology offers a unique and directly applicable capability.

Early developments of fracture mechanics focused on plane-strain or essentially linear elastic fracture conditions (LEFM) and on relatively high strength brittle materials such as aircraft structures, missile cases, gun tubes, etc. Soon the technology was extended to include fatigue and stress corrosion crack propagation. Later on, because of the recognized limitations in the applicability of LEFM, considerable effort was devoted to extend the fracture mechanics technology to encompass situations involving considerably more plasticity than is permissible under LEFM conditions. As a result the break through came in the form of the path independent J-integral, a field parameter analogous to K in LEFM. The general usefulness of the technology has thus been extended to a much broader spectrum of applications and materials: lower strength, higher localized stress regions, low cycle fatigue and creep controlled crack growth. Even more recently, the technology has taken another major step forward with the advent of J resistance curves, tearing modulus concepts and tearing instability model~. These recent developments offer the capability to predict the permissible amounts of stable crack growth in the ductile temperature regime, and the eventual instability conditions for the catastrophic failure of the structure by ductile tearing under fully plastic conditions. More important these recent advances in technology offer the promise of enabling the design of structures and selection of materials so as to avoid any possibility of failure due to ductile tearing instability.

In short, fracture mechanics provides engineers with a powerful new tool for more effective design pertaining to structural reliability; it therefore seems logical that it should be an important part of the Navy's titanium program.

The overall objective of this program is to assist the Navy in developing and applying advanced fracture mechanics technology to ensure structural integrity in critical applications of titanium alloys. To achieve this the following objectives must be met:

1) Identification of Areas of Concern and Data Availability
2) Assimulation of Pertinent Information of Structures
3) Performance Structural Analysis and Recommendations

2. TECHNICAL PROGRESS

A) Technical Meetings

The first phase of the program is "Assimilation of Pertinent Information and Data". The work during this reporting period was devoted to that task. In order to gather this information and data, seven meetings were held between members of the Westinghouse program team and Navy technical personnel at a number of different Navy facilities. Also, Westinghouse participated in a ONR Ti-100 Workshop (review meeting held at the Naval Academy, Annapolis). The following is a chronological listing of these meetings with a list of persons attending and a brief description of the subjects covered.

1) June 25-26, 1980 - ONR Ti-100 Workshop/Review at the Naval Academy, Annapolis, MD.
   - Westinghouse Participants
     - -- E. T. Wessel
     - -- J. D. Landes
     - -- H. A. Ernst
   - J. D. Landes made a presentation at the Workshop. Since the program was just beginning he discussed the program background, objectives and proposed methods for approaching the subject.
2) June 27, 1980 - Meeting at DTNSRDC, Annapolis, MD.
   - Navy Participants
     - -- J. P. Gudas
     - -- J. A. Joyce
     - -- M. G. Vassilaros
   - Westinghouse Participants
     - -- J. D. Landes
     - -- H. A. Ernst
     - -- G. A. Clarke

- At this meeting general concerns of the Navy regarding fracture prediction for Ti-100 were discussed as well as possible objectives and approaches for this program. Emphasis was given to the need for a new approach to fracture analysis based on the state of the art technology. The Westinghouse personnel were given a tour of some of the DTNSRDC facilities for fracture testing. Also suggestions were made for possible future discussions.

3) July 11, 1980 - Meeting at DTNSRDC, Carderock, MD.
   - Navy Participants
     - -- J. P. Gudas
     - -- I. L. Caplan
     - -- M. Krenzke
     - -- T. Kiernan
     - -- A. J. Wiggs
     - -- L. N. Gifford
     - -- P. Dudt
   - Westinghouse Participants
     - -- E. T. Wessel
     - -- J. D. Landes
   - At this meeting applications and approaches to model testing were discussed including some suggestions for model analysis. A tour of facilities for model testing was given to the Westinghouse personnel.

4) July 31, 1980 - Meeting at NAVSEA, Crystal City, VA.
   - Navy Participant
     - -- R. Provencher
   - Westinghouse Participants
     - -- E. T. Wessel
     - -- J. D. Landes
   - At this meeting design philosophy was discussed with emphasis on suggestions for improving present approaches to design against failure.

5) July 31, 1980 - Meeting at NRL, Washington, D.C.

- Navy Participants
  - -- R. Judy
  - -- J. Goode
- Westinghouse Participants
  - -- E. T. Wessel
  - -- J. D. Landes
- At this meeting fracture related materials data for Ti-100 was discussed. NRL presented some reports of their latest work on this alloy.

6) August 1, 1980 - Meeting at DTNSRDC, Carderock, MD.

- Navy Participants
  - -- T. Kiernan
  - -- A. J. Wiggs
  - -- L. N. Gifford
  - -- P. Dudt
- Westinghouse Participants
  - -- E. T. Wessel
  - -- J. D. Landes
- At this meeting topics discussed at the July 11 meeting relating to model testing were explored in more detail.

7) November 7, 1980 - Meeting at DTNSRDC, Annapolis, MD.

- Navy Participants
  - -- I. L. Caplan
  - -- O. P. Arora
  - -- H. P. Chu
  - -- D. Daves
- Westinghouse Participants
  - -- J. D. Landes
  - -- H. A. Ernst
- At this meeting Westinghouse personnel discussed some of the results from previous meetings and presented a list of important areas relating to advanced fracture analysis which could be incorporated into the program. Materials

property data which would be needed for this program was discussed. Some of these data were made available and other sources of data were identified. An additional trip to this Laboratory is planned for the near future to discuss some addition materials property data.

8) November 7, 1980 - Meeting at the Naval Surface Weapons Center, White Oak, Silver Springs, MD.
   - Navy Participant
     -- D. Nickelson
   - Westinghouse Participants
     -- J. D. Landes
     -- H. A. Ernst
   - Mr. Nickelson is a fracture expert at this center. Although his concern is for a different application than that of the present program, his viewpoint on approaches to fracture analysis in the Navy was an important input for this program.

B) <u>Information and Data</u>

As a result of these meetings, many areas were identified as having significance to the problem of structural integrity analysis for Ti-100 and questions were raised regarding these areas. A list of areas identified follows:

1) Toughness - How much toughness is enough? How should toughness be characterized for structural analysis?
2) Dynamic Loading - What is the fracture behavior under dynamic loading rates? Can the parameters used for conventional fracture analysis also be used under dynamic loading?
3) Fatigue - Can fatigue to failure be analyzed? What is the effect of zero to compression loading on fatigue crack growth analysis?
4) Low Cycle Fatigue - What is the effect of this on crack initiation and growth?
5) Failure Criteria - No failure criterion is presently used. Can one be identified particularly for analyzing fatigue to failure?

6) Crack Growth Under Sustained Load - This phenomenon has been observed in the form of subcritical cracking and delayed failure. Is this related to environmental influences, creep or time dependent fracture toughness behavior?
7) Effect of Prestrain on Fracture Behavior - How is fracture toughness and other fracture behavior influenced by an initial prestrain?
8) Effect of Residual Stresses in Welds - How can these be measured and how can they be incorporated into a structural integrity analysis?
9) Thickness Effects - How are these accounted for in structural analysis?
10) Scale Models vs. Real Structures - How well do scale models predict fracture behavior in real structures? What models are the most appropriate ones to analyze?
11) Shop Fabrication vs. Field Fabrication - Are properties in field welded structures as good as those in shop welded structures?
12) Explosion Bulge and Tear Tests - What significance do these have; Can they be analyzed using advanced fracture approaches?

From this list of concerns four specific areas were identified for immediate future consideration.

1) Analysis of model test components.
2) Static versus dynamic fracture characterization and analysis.
3) Analysis of fatigue to failure with the consideration of a failure criterion.
4) Creep and delayed fracture.

Data is presently being gathered relating to these areas. The present plan is to select some model components to conduct a preliminary fracture analysis using data already available. From this analysis insight should be gained relative to the questions of how critical will design against fracture be for proposed structures using Ti-100, how well do advanced fracture concepts apply to these cases, how can future fracture analysis be improved, what additional materials property data will be needed. When these questions are answered a more refined analysis can be made leading to recommendations to the Navy for incorporating advanced fracture concepts into their reliability analysis

3. CONCLUSIONS AND RECOMMENDATIONS

Numerous meetings were held with Navy personnel in order to identify areas of concern and the experimental data needed for the structural analysis. The mentioned areas cover a broad spectrum regarding loading conditions, material behavior, fabrication procedures, weldments and structural integrity. It is anticipated that some data needed might not be available in which case recommendations will be made regarding the data gathering and/or critical tests for the specific needs.

Future plans for this program include further discussions and exchanges with Navy personnel to identify critical areas, accumulate materials property data and identify pertinent structures to be analyzed and to conduct the appropriate analyses and make recommendations for structural reliability.

APPENDIX

As a result of the mentioned meetings, several technical documents were exchanged and discussed between Navy personnel and Westinghouse program team members. The reports include:

1. Gudas, J., "J-R Curve for Ti-100", private communication, October 1980.
2. Cox, J. E. and Judy, R. W., "Sustained Load Subcritical Crack Growth in Ti-6Al-2Cb-1Ta-0.8Mo (Ti-6211)", Second Semiannual Report to DTNSRDC, Annapolis, Naval Research Laboratory, June 1980.
3. Judy, R. W. and Goode, J. W., "Structural Integrity Related Properties of 2-in. (5.1 cm) Thick Ti-100 as Influenced by Plate Processing Variables", Naval Research Laboratory Memorandum Report 3401, November 1976.
4. Cares, W. R. and Crooker, T. W., "Fatigue Crack Growth of Ti-6Al-2Cb-1Ta-0.8Mo Alloy in Air and Natural Sea Water Environments", Naval Research Laboratory Memorandan Report 2617, June 1973.
5. Crooker, T. W. and Yoder, G. R., "Sustained-Load Cracking of Ti-6Al-2Cb-1Ta-0.8Mo in Ambient Air," Naval Research Laboratory Memorandum Report 2686, November 1973.
6. Judy, R. W. and Goode, R. J., "Criteria for Fracture Prevention in Titanium Structures", Naval Research Laboratory Memorandum Report 3434, December 1976.
7. Davis, D. A., "Fatigue Crack Growth for Ti 621/0.8", private communication October 1980.
8. Davis, D. A., "Low-Cycle Fatigue Crack Propagation in Ti-6Al-2Cb-1Ta-0.8Mo Alloy", David Taylor Naval Ship R&D Center, Report SME-79-120, May 1980.
9. Gifford, L. N. and Wiggs, A. J., "Plan for FV-80 Submarine Hull Toughness Research Effort", DTNSRDC Report, March 1980.