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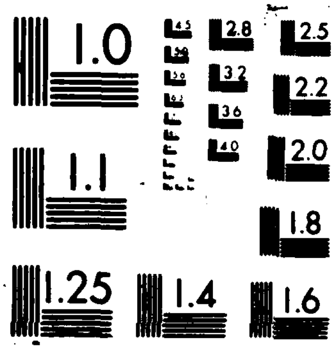

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The optimal use of advanced beta and near-beta titanium alloys, in situations involving dynamic or shock loading, requires an understanding of how both microstructure and loading rate influence the fracture behavior. To address this need, SRI is performing dynamic crack initiation and propagation experiments on Ti-10V-2Fe-3Al in three microstructural conditions, varying the loading rate to establish the rate-dependence of the fracture toughness. A new experimental method, developed in a previous Air Force Office of Scientific Research program (the one-point-bend impact test) and advanced instrumentation techniques (optical and Hall effect displacement transducers) are used to measure the dynamic initiation and propagation toughness. Further, the Fracture Surface Topography Analysis (FRASTA) technique, a novel quantitative fractography technique, is

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applied to the fractured specimens to elucidate the microstructural failure mechanisms controlling fracture in each of the investigated microstructures.

This report summarizes the progress made during the first year of the program. A metallurgical investigation has been completed to determine the appropriate heat treatments to produce three microstructures with 0%, 12%, and 40% of primary alpha phase, and with a strength level of about 1300 MPa. The uniformity of the resulting microstructures has been established and their tensile properties measured. We have also verified that no embrittling omega phase precipitated during heat treatment.

An optical technique to measure crack opening displacements (COD) during dynamic fracture experiments has been developed. The COD histories will be correlated with the FRASTA observations to establish the kinetics of microdamage during crack initiation and propagation.

Finally, numerical algorithms have been implemented in SRI's finite element computer codes to compute the stress intensity factor in simulations of the dynamic fracture experiments.

In the next months we will complete the dynamic fracture experiments and establish the variation of toughness with loading rate and microstructures (percent primary alpha phase). We will also initiate the topographic analysis of selected specimens to correlate the observed fracture behavior with microstructural failure processes.

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February 1987

SRI International
First Annual Report

INFLUENCE OF MICROSTRUCTURE AND MICRODAMAGE PROCESSES ON FRACTURE AT HIGH LOADING RATES

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I SUMMARY

The optimal use of advanced beta and near-beta titanium alloys, in situations involving dynamic or shock loading, requires an understanding of how both microstructure and loading rate influence the fracture behavior. To address this need, SRI is performing dynamic crack initiation and propagation experiments on Ti-10V-2Fe-3Al in three microstructural conditions, varying the loading rate to establish the rate-dependence of the fracture toughness. A new experimental method, developed in a previous Air Force Office of Scientific Research program (the one-point-bend impact test) and advanced instrumentation techniques (optical and Hall effect displacement transducers) are used to measure the dynamic initiation and propagation toughness. Further, the Fracture Surface Topography Analysis (FRASTA) technique, a novel quantitative fractography technique, is applied to the fractured specimens to elucidate the microstructural failure mechanisms controlling fracture in each of the investigated microstructures.

This report summarizes the progress made during the first year of the program. A metallurgical investigation has been completed to determine the appropriate heat treatments to produce three microstructures with 0%, 12%, and 40% of primary alpha phase, and with a strength level of about 1300 MPa. The uniformity of the resulting microstructures has been established and their tensile properties measured. We have also verified that no embrittling omega phase precipitated during heat treatment.

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II INTRODUCTION

The U. S. Air Force is making a considerable effort to develop new weapons systems that perform better, are less costly to produce and maintain, and have greater survivability. One key to achieving these goals is the introduction of new advanced materials in Air Force structures.

Because of their attractive strength-to-weight ratio and their good formability, advanced beta and near-beta titanium alloys are finding increasing use in aircraft structural components. These alloys are often used in fracture-critical applications, where they are subjected to dynamic loads. Landing gear and wing frame parts are typical examples of such applications involving dynamic loads.

Therefore, understanding the dependence of fracture toughness on loading rate is an important aspect of evaluating advanced titanium alloys for specific applications. Moreover, because of the large variety of microstructures that can be produced from the same alloy composition, an understanding of how microstructure influences the fracture behavior is also of great importance for the efficient use of these alloys.

The research program being conducted at SRI International addresses these needs by investigating the dependence on loading rate and microstructure of the fracture behavior of a promising advanced titanium alloy, Ti-10V-2Fe-3Al. This annual report reviews the specific objectives of the program and summarizes SRI's progress during the first year of work.

III OBJECTIVES AND APPROACH

Objectives

To establish how loading rate and microstructure influence fracture behavior in advanced titanium alloys, we are conducting a 3-year research program with the following specific objectives:

(1) Establish the variation of the initiation toughness K_{Id} with loading rate, and the variation of the propagation toughness K_{ID} with crack speed for a family of Ti-10V-2Fe-3Al microstructures.

(2) Characterize the micromechanisms of failure for each investigated microstructure, loading rate, and crack velocity; determine the microstructural parameters that control these mechanisms; and obtain independent, microstructurally based toughness estimates using measurements of local crack opening displacement and fracture surface roughness.

(3) Develop a model of dynamic fracture incorporating the influence of microstructure on microdamage processes, and explain the observed behavior of the toughnesses K_{Id} and K_{ID} with changes in microstructure, loading rate, and crack velocity in terms of this model.

Approach

To achieve the program's objectives, we are applying advanced experimental methods developed in a previous AFOSR program [1] and a new topographic technique for deducing microfailure activity from fracture surfaces to Ti-10V-2Fe-3Al alloy in several microstructural conditions. To characterize the dynamic fracture behavior in terms of continuum fracture mechanics parameters (such as the stress-intensity factor), we are conducting crack initiation and propagation experiments at several loading rates, using the impact one-point-bend test. In selected cases, we are also performing numerical simulations of the experiments. We apply the Fracture Surface Topography Analysis (FRASTA) technique to the fractured specimens to obtain the crack opening displacement directly from microscopic measurements.

The FRASTA technique also allows us to establish which microstructural features control the nucleation, growth, and coalescence of microcracks or microvoids, and ultimately lead to macroscopic crack extension. These correlations are expected to provide guidance in selecting the optimum microstructure for the Ti-10V-2Fe-3Al alloy system. By correlating the fractographic observations with the toughness measurements (in terms of stress-intensity and crack opening displacement), we can determine and model how microstructure and microdamage processes affect fracture at high strain rates. By comparing the toughness results derived from continuum measurements (stress-intensity factor) and from fracture surface observations (crack opening displacement), we can then determine whether the concept of stress-intensity is still valid for fracture at very high loading rates, or whether new or modified fracture criteria have to be introduced.

IV PROGRESS

During the first year of the program, we procured the Ti-10V-2Fe-3Al alloy and performed an extensive metallurgical investigation to select and characterize the microstructures for the fracture tests. We prepared and instrumented all the specimens for both the crack initiation and the crack propagation experiments. Finally, we developed the experimental and analytical tools needed to record and analyze the experimental data. Accounts of these various tasks are provided in this section.

Microstructural Selection and Investigation

Microstructural Selection

Guided by a literature review of the metallurgy of Ti-10V-2Fe-3Al and by discussions with Dr. T. Duerig, who is acting as a consultant for this program, we selected the microstructural variations for our investigation.

For the main program effort, we have decided to investigate how, for a given strength level, variations in the primary alpha content (α_p) affect dynamic fracture properties. We are investigating microstructures with 0%, 12%, and 40% α_p, at a strength level of approximately 1200 to 1300 MPa. The microstructure with 40% α_p, and aged for 8 hours at 500°C was chosen as the base-line microstructure, and it will be studied most extensively. This is because this microstructure corresponds to the commercially recommended heat treatment.

If time and funds permit, we will also investigate how, for a given α_p content and strength level, the beta (β) grain size influences the dynamic fracture behavior. A plate of material that has undergone a special thermomechanical treatment to refine the grain size has been set aside for this purpose.

Microstructural Investigation and Results

We performed a microstructural investigation of the material purchased for the program in order to establish the precise heat-treatment conditions needed to achieve the selected microstructures. The specific objectives of the microstructural investigation were to:

(1) Establish the beta-transus temperature of the alloy.

(2) Establish the dependence of the α_p content on the solution temperature.

(3) Establish the aging response curve for microstructures with various amounts of α_p.

(4) Determine the occurrence of compositional variations (beta fleck) in the rolled plates.

(5) Assess the influence of oxygen contamination on the mechanical properties.

(6) Ascertain that no embrittling isothermal omega (ω) phase was present in the selected microstructures.

We have established that the beta-transus temperature for our particular alloy composition is between 810° and 815°C. Furthermore, we established by the point count grid method that solution treatment at 790°C and 760°C resulted in 12% and 40% α_p, respectively. The aging responses of materials solution treated at 825°C, 790°C, and 760°C are shown in Figure 1, which plots Vickers hardness as a function of time and aging temperature. For a given aging temperature, all microstructures rapidly reach a peak hardness and then slowly soften with time.

Based on these results, the three heat treatments for obtaining the desired microstructures were established as:

(1) Solution treatment at 760°C for 1 hour; water quenched; aged in a salt bath at 500°C for 8 hours (40% α_p). This process corresponds to the recommended commercial heat treatment.

(2) Solution treatment at 790°C for 1 hour; water quenched; aged in a salt bath at 535°C for 2.5 hours (12% α_p).

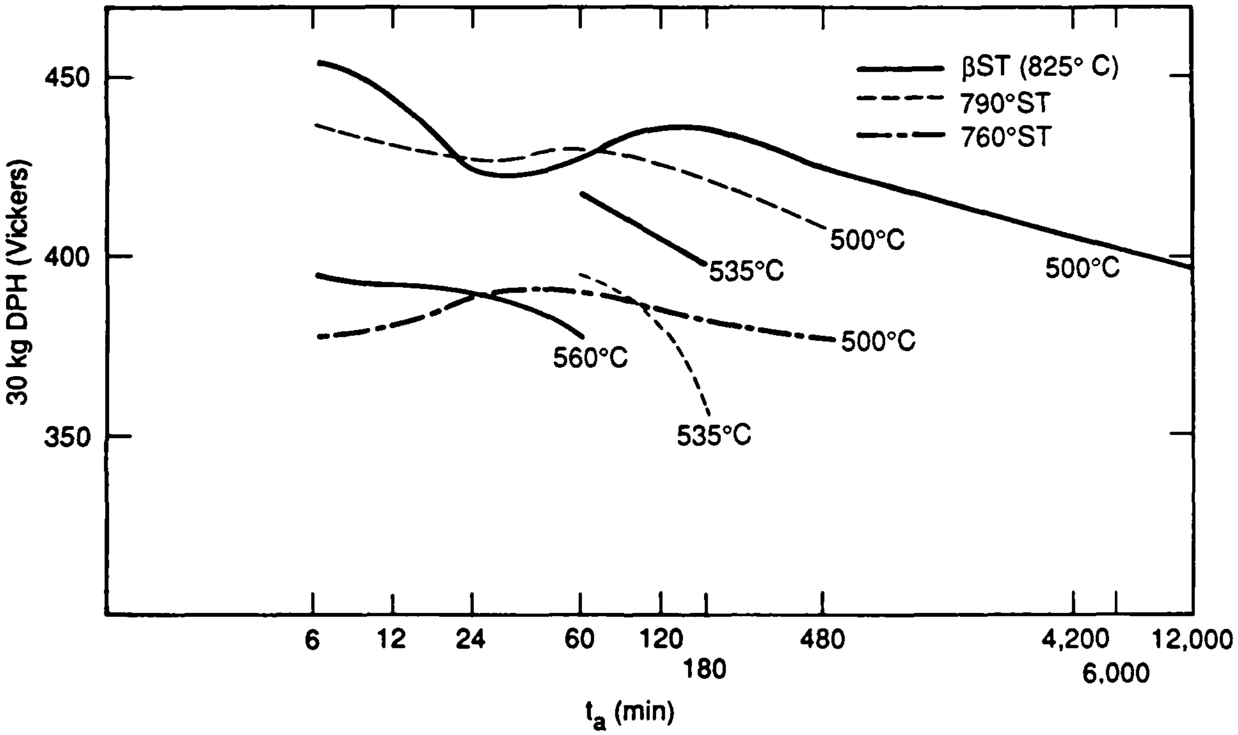

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FIGURE 1 AGING CURVES FOR Ti-10V-2Fe-3Al SOLUTION TREATED AT 760°C, 790°C AND 825°C (βST)

(3) Solution treatment at 825°C for 1 hour; water quenched; aged in a salt bath at 560°C for 1 hour (0% α_p).

Figure 2 shows the engineering stress-strain curves for the material heat treated according to these three schedules.

Ramdom checking of the as-received microstructure in several plates indicated that macrosegregation (beta-fleck) was not a problem for the material acquired for the program, except toward the edges of the plates. However, preliminary tensile tests of material heat treated according to the three schedules chosen for the program resulted in very low ductilities compared with values anticipated from published data.

Two possible reasons for the poor ductilities were investigated: (1) the precipitation of the embrittling ω phase during the aging treatment, and (2) oxygen contamination. X-ray diffraction analyses of the broken tensile specimens showed no signs of ω phase. However when a new series of tensile tests was run on specimens that had been previously ground to remove the oxygen-contaminated surface layer, a significant improvement in ductility was observed. We therefore concluded that oxygen contamination, even if restricted to a thin surface layer, may have a highly detrimental effect on the properties of the alloy. Consequently, all tensile and fracture specimens used in the program are being ground after heat treatment to remove the oxygen-contaminated layer.

Development of Experimental and Analytical Tools

Development of an Optical Crack Opening Displacement Transducer

To reconstruct the microstructural failure process with the FRASTA technique, topographic maps of the two fracture surfaces are computationally superimposed and then gradually separated. During separation, the appearance of microcracks and microvoids near and ahead of the main crack are recorded, and this information can be used to develop microdamage models.

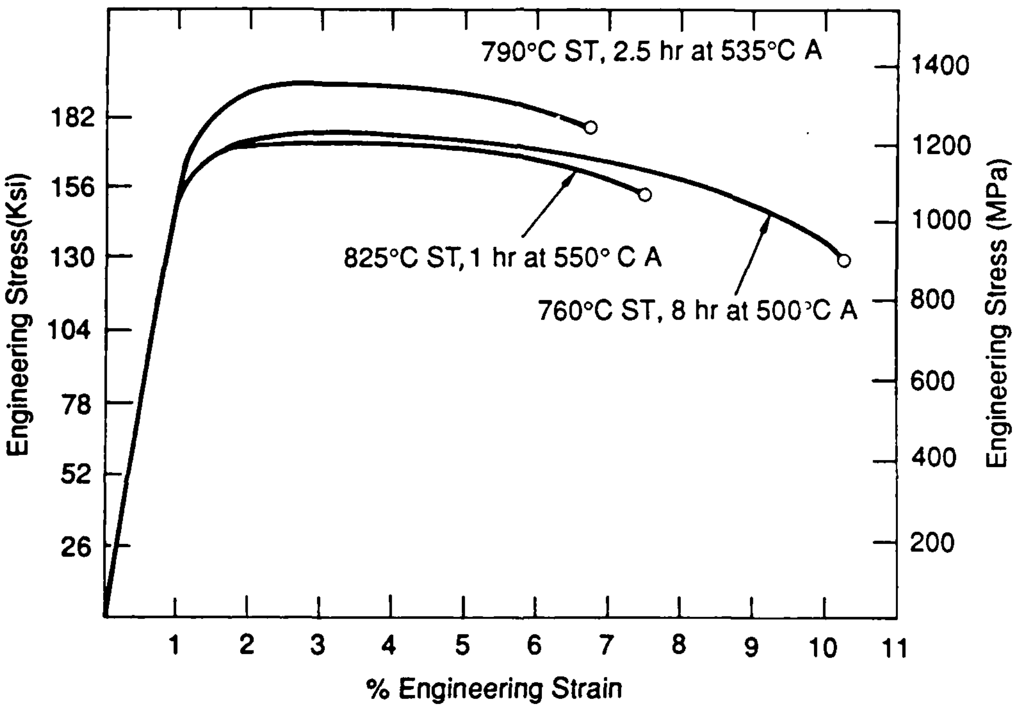

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FIGURE 2 ENGINEERING STRESS - STRAIN CURVES FOR Ti-10V-2Fe-3Al HEAT - TREATED ACCORDING TO THE THREE SELECTED SCHEDULES

In the case of dynamic fracture, for which loading rate effects and microdamage incubation times may be important, it would be desirable to correlate the post-mortem fracture surface separation used in the FRASTA technique with the actual crack face opening history. This can be accomplished by performing dynamic crack face opening displacement measurements during the fracture experiments. For that purpose, we are adapting optical crack opening displacement transducers, originally developed by Zimmermann and Demler [2] for quasi-static experiments, to dynamic fracture experiments. The method consists of mounting, end to end and coaxially, two optical fibers across the crack face, and shining a laser beam through these fibers. As the crack faces separate, the fibers also separate and the intensity of the light transmitted through the interface of the fibers decreases. The crack opening displacement is measured by measuring the transmitted light intensity. We built a prototype of the transducer and tested it under quasi-static conditions, and we are preparing to test it under dynamic conditions. We plan to use up to three such transducers during the fracture experiments. Initially, the transducers will be mounted on the specimen surface and along the crack faces. If time and funds permit we will also attempt to perform crack opening displacement measurements at the center of the specimen by mounting the optical fibers in small longitudinal holes drilled through the specimen.

Numerical Algorithm to Calculate the Dynamic Stress-Intensity Factor

In the dynamic crack initiation and propagation experiments, the stress-intensity factor and hence the toughness, will be directly measured using the strain gage method used in the previous AFOSR-sponsored program [1]. It is important, however, to verify the strain gage measurements by performing numerical simulations of the experiments and by calculating the dynamic stress-intensity factor.

During the first year we incorporated into SRI's dynamic finite element codes the algorithms required to evaluate the dynamic stress-intensity factor during numerical simulations of the experiments. The method consists of calculating the dynamic energy release rate using a contour integral formulation proposed by Nakamura, Shih, and Freund [3]. The dynamic energy release rate is then related to the stress-intensity factor using theoretical expressions derived by Nishioka and Atluri [4].

In simulating the crack propagation experiments, it is necessary to let the crack grow through the finite element mesh using a node release technique. To avoid spurious oscillations in the calculated stress-intensity history that arise when nodal forces are abruptly reduced to zero, a special node release algorithm was also incorporated.

Simulations of dynamically loaded crack problems for which closed-form solutions are available have demonstrated that the algorithms perform adequately, and hence that reliable dynamic stress-intensity values can be calculated.

Future Work

We are currently completing preparations for the dynamic fracture experiments; testing will begin in the next few weeks. A matrix of the planned experiments is shown in Table 1. Initiation tests will be performed at four different loading rates--quasi-static (QS), low rate (LR), intermediate rate (IR), and high rate (HR)--covering a stress-intensity rate range of 10^{-3} to 10^{6} MPa $m^{1/2}$ s^{-1}. Crack initiation specimens will be instrumented with a strain gage near the crack tip. Selected experiments will also be instrumented with optical crack opening displacement transducers. For the one-point-bend propagation tests, the crack tip acuity and the impact velocity will be varied to achieve different crack speeds, and the specimens will be instrumented with strain gages and crack opening displacement transducers. The crack velocity will be measured using high-speed photography, and the impact load will be recorded using an instrumented hammer. Crack velocity and impact load history will serve as input for the numerical simulations.

Table 1: Matrix of Fracture Experiments

Microstructure	Initiation Tests QS	Initiation Tests LR	Initiation Tests IR	Initiation Tests HR	Propagation Tests
40% α_p	4	4	6	8	6
12% α_p	2		3	4	2
0% α_p	2		3	4	2

We anticipate that the fracture experiments will be completed by the end of 1987. The FRASTA work will start as soon as the first fractured specimens become available and will be pursued for the next 18 months. Numerical simulations of the experiments will also be initiated as soon as the experimental input data become available, and they will be pursued during the third year of the program concurrently with the metallographic and fractographic analysis and the modelling work.

V PUBLICATIONS AND PRESENTATIONS

Papers prepared or published and presentations made during SRI's previous AFOSR-sponsored programs are listed below.

Publications

J. F. Kalthoff and D. A. Shockey, "Instability of Cracks Under Impulse Loads," J. Appl. Phys. 48, 984-993 (March 1977)

D. A. Shockey, J. F. Kalthoff, H. Homma, and D. C. Erlich, "Criterion for Crack Instability Under Short Pulse Loads," Advances in Fracture Research, D. Francois et al., Eds. (Oxford and Pergamon Press, New York, 1980), pp. 415-423.

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Presentations

D. C. Erlich and D. A. Shockey, "Instability Conditions for Cracks Under Short-Duration Pulse Loads," Topical Conference on Shock Waves in Condensed Matter, Meeting of the American Physical Society, Washington State University, Pullman, WA, June 11-13, 1979.

D. A. Shockey, "Instability Conditions for Cracks Loaded by Short Stress Pulses," Poulter Laboratory Seminar, SRI International, Menlo Park, CA, December 12, 1979.

D. A. Shockey, "Dynamic Crack Instability," Institut CERAC, Ecublens, Switzerland, May 19, 1980.

D. A. Shockey, "Dynamic Crack Instability," Institut für Werkstoffmechanik, Freiburg, Germany, May 21, 1980.

D. A. Shockey, "Simultaneous Measurements of Stress Intensity and Toughness for Fast Running Cracks in Steel," Poulter Laboratory Seminar, SRI International, Menlo Park, CA, June 1980.

D. A. Shockey, "Criterion for Crack Instability Under Short Pulse Loads," Fifth International Conference on Fracture (ICF5), Cannes, France, March 29-April 3, 1981.

D. A. Shockey, "Simultaneous Measurements of Stress Intensity and Toughness for Fast Running Cracks in Steel," 18th Annual Meeting of the Society for Engineering Science, Inc., Brown University, Providence, RI, September 2-4, 1981.

D. A. Shockey, "Short Pulse Fracture Mechanics," Seminar for the Department of Applied Mechanics, Stanford University, Stanford, CA, March 3, 1983.

D. A. Shockey, "Short Pulse Fracture Mechanics," Poulter Laboratory Seminar, SRI International, Menlo Park, CA, April 11, 1983.

J. H. Giovanola, "Mechanics of Fracture Under Pulse Loads; Minimum Time Theory Revisited," Poulter Laboratory Seminar, SRI International, Menlo Park, CA, April 1984.

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J. H. Giovanola: "Fracture of High Loading Rates," presented at the University of California Berkeley Short Course, Fracture and Fatigue: Approaches for Analysis and Control of Failure, June 1986.

List of Personnel

Dr. D. A. Shockey, Principal Investigator
Dr. J. H. Giovanola, Principal Investigator
Mr. A. T. Werner, microstructural investigation
Dr. R. W. Klopp, development of optical COD transducer
Dr. J. Lemonds, numerical analysis
Dr. T. Duerig, consultant

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