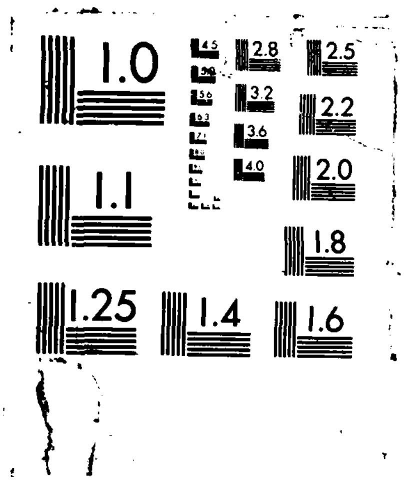
AD-A189 429 DUCTILE FAILURE(U) BROWN UNIV PROVIDENCE RI 1/1

A S KUSHNER 28 SEP 87 N00014-86-K-0262

UNCLASSIFIED F/G 11/6.1 NL


1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
4.5
5.0
5.6
6.3

September 28, 1987

To: Dr. R.E. Whitehead, Director, Mechanics Division, Office of Naval Research
From: A. Needleman, Brown University, Providence, RI
Re: Yearly Summary of Research for FY87

Title: Ductile Failure
Contract Number: N00014-86-K-0262
Work Unit Number: 4324-771
Scientific Officer: Dr. A.S. Kushner

Research Summary

The aim of this work on ductile failure is to provide a framework for quantitatively relating macroscopic measures of fracture toughness and ductility to micro-structural mechanisms of ductile fracture. Microvoid nucleation and growth is the principal mechanism of ductile fracture in metals; the voids mainly nucleate at second phase particles, by particle cracking or by decohesion of the particle-matrix interface, and final rupture involves the growth of neighboring voids to coalescence. Although the role of void nucleation and growth in ductile failure of metals is now well known, the details of the mechanism governing this failure process are not fully understood. A detailed characterization of porosity evolution is necessary to relate microstructural descriptions of the ductile rupture process quantitatively to macroscopic measures of ductility.

We have carried out analyses of ductile fracture processes that use continuum constitutive relations incorporating physically based models of the micro-rupture process; i.e. models of the nucleation, growth and coalescence of microvoids. The material's constitutive description allows for the possibility of a complete loss of stress carrying capacity with the associated creation of new free surface, without any additional failure criterion being employed. Thus, fracture arises as a natural outcome of the deformation process. This contrasts with the usual approach to fracture analysis where the constitutive characterization of the material and a fracture criterion are specified separately. These numerical studies have been carried out in conjunction with experimental investigations in order to provide precise quantitative comparisons between the theoretical predictions and experimental observations.

In one study, carried out in collaboration with Dr. Owen Richmond of Alcoa and Dr. V. Tvergaard of The Technical University of Denmark, the development of porosity and its effects on strength at high stress triaxialities was examined through experiments on U-notched bars and numerical modelling. The material used is the same as that used previously by Spitzig et al. (*Acta Metall.*, in press) to study the effects of porosity in uniaxial tensile tests. Our tests complement the results of Spitzig et al. by providing data on void growth and strength at higher stress triaxialities. Void volume fraction measurements, made on sections cut from specimens deformed to various strains, trace the history of void growth under conditions of high stress triaxiality. Comparison of the load extension curves at various notch acuities provided information on the effects of hydrostatic stress on strength reduction.

The calculations are based on a rate dependent version of the constitutive relation introduced by Gurson (Brown University Ph. D. thesis, 1975). This model has been used in previous analyses of ductile fracture processes in which observed failure behaviors have been qualitatively reproduced in considerable detail. In particular, the cup cone fracture in an axisymmetric tensile specimen, shear failure in a plane strain tensile specimen and ductile fracture between particles ahead of a crack tip are all qualitatively predicted by this constitutive relation.

The only experimentally determined quantities input into the calculations are the uniaxial stress-strain curve for the matrix material and the initial void volume fraction. The parameters entering the porous plastic constitutive description have been chosen to provide a reasonable fit of both strength and void growth predictions with results of micro-mechanical models of periodic arrays of voids. While the parameters could have been chosen to fit experimental observations, our aim was to evaluate a model for porous plastic solids which is based solely on micro-mechanical modelling, without biasing the predictions toward the experimental results, in order to assess the capability of analyses carried out within the Gurson porous plastic constitutive framework to predict void growth and failure phenomena for a range of triaxial stress states. Our results show good quantitative agreement between the calculations and experiment for the evolution of void volume fraction and for the effects of void growth on strength. Key issues that need to be addressed in improving the modelling capability are the matrix material constitutive characterization and improved quantification of void nucleation phenomena and non-uniform void distribution effects.

These experimental results also formed the basis for Becker's investigations of non-uniform void volume fraction effects. The effects of the non-uniformity of the defect distribution were investigated by discretizing a volume of material. Based on experimental observations of porosity in sintered iron specimens, each subregion was assigned a defect density. Deformation of the region through the entire failure process is analyzed and the numerical results show the strong role played by the micro-inhomogeneity in limiting ductility. Becker found little influence of the nonuniformity of the distribution on the stress-strain response but a rather large effect of distribution on the strain to failure initiation.

In collaboration with Professor S. Suresh of Brown University, Dr. V. Tvergaard of The Technical University of Denmark, and Dr. A.K. Vasudevan of Alcoa, ductile failure by grain boundary void growth was investigated. This phenomenon is readily identified by the presence of grain boundary precipitates and microvoid dimples and is distinct from the brittle grain boundary fracture process arising from the segregation of harmful impurities to the grain boundary which usually exhibits a microscopically smooth grain boundary fracture. Despite the wide range of evidence now available in the literature for ductile failure by grain boundary void growth and its role in determining the fracture properties of precipitation hardened alloys, the mechanisms and implications underlying this process have not been widely appreciated. Grain boundary cavitation at high temperatures has been the subject of many in depth investigations, but prior to our investigation, the dependence of macroscopic fracture behavior at room temperature on the microscopic details of grain boundary precipitation and void growth at the grain boundary had not received a detailed theoretical treatment.

The aim of this study was two-fold: (i) to identify the microstructural features which control the macroscopic fracture properties; and (ii) to predict the dependence of macroscopic toughness measures, i.e., J_{IC} and the tearing modulus, for a particular model system, in terms of parameters characterizing the grain boundary ductile fracture mechanism operating on the microscale, e.g., grain size, void nucleating particle size and strength. A high purity Al-3 wt.% Li alloy, suitably heat treated to produce a predominantly intergranular ductile fracture, was used as a model material. The fracture mechanism for the microstructures investigated, ductile void growth with voids nucleating from grain boundary precipitates, was well documented in several recent studies (Suresh, Vasudevan, Tosten and Howell, *Acta Metall.*, **35**, 25, 1987; Vasudevan and Doherty, *Acta Metall.*, **35**, 1193, 1987).

These calculations were also carried out within the continuum constitutive framework for progressively cavitating solids due to Gurson. Due to the difference in size scale, the situation analyzed here is quite different from that prevailing in the notched bars. Even for the most sharply notched bars, microstructural features are small compared to lengths characterizing gradients of the stress and deformation fields. At a crack tip, however, the relevant microstructural size scales are large compared to the gradients. Hence, a characteristic material length scale must enter the formulation, if only from dimensional considerations. There are two relevant microstructural size scales considered in the analyses; one characterizing the grain size and the other associated with the grain boundary void nucleating zone. Our analyses showed that the thickness of the grain boundary porous zone plays a major role in determining the overall fracture properties.

Full J-resistance curves are calculated and for this purpose modelling the complete specimen geometry is important to account for changes in loading configuration at the crack for the large amounts of crack growth needed. The grain boundary particles are modelled through the spatial distribution of the amplitude of the void nucleation function. Void nucleation is only possible within a grain boundary void nucleating zone, with the thickness of this zone set by the particle spacing. The full specimen model involves resolving features on the size scale of a few grain boundary particle spacings but is still highly idealized, in terms of the grain boundary porous zone, and also with regard to implicit assumptions about the material properties and the geometric configuration. Nevertheless, noting the absence of "adjustable" parameters and bearing in mind the limitations of the model, the quantitative agreement between the model predictions and the experimentally measured K_{IC} and tearing modulus values is quite good; the predicted K_{IC} values are within a factor of two of the experimental values, while the predicted and observed values of the tearing modulus are typically within 50% of each other. Although the comparison between calculation and experiment is phrased in terms of K_{IC} and tearing modulus, the limitations of these quantities for characterizing crack growth versus crack driving force response was discussed. What characterizes the toughness is the J-resistance curve which, however, is expected to be at least somewhat specimen dependent.

In collaboration with Dr. V. Tvergaard of The Technical University of Denmark, the influence of temperature on absorbed energy in the Charpy V-notch test was investigated using material properties representative of a particular high nitrogen steel. The analysis is based on a constitutive relation incorporating models of the competing failure mechanisms of ductile void growth and slip induced cleavage. Ductile fracture by the nucleation and growth of micro-voids is described within the porous plastic constitutive framework introduced by Gurson. The formation of cleavage microcracks is accounted for in a more approximate fashion, by assuming that cleavage cracks initiate when the maximum principal stress reaches a temperature independent critical value. Most of the computations were based on a quasi-static formulation since, even at the strain rates encountered in the Charpy impact test, material strain rate sensitivity is the main time effect. The influence of material inertia was investigated in a few transient analyses. Dynamic effects give rise to a maximum plastic strain rate at the notch root that is a factor of 2 to 3 larger than predicted by a quasi-static analysis. Because of material strain rate sensitivity this leads to correspondingly higher stresses there; still, with a representative strain rate hardening exponent of 0.01, a factor of 3 difference in strain rate only gives a factor of $3^{0.01} \approx 1.01$ difference in stress level. The dynamic analyses indicate that, at least when fracture initiates after general yielding, there is little effect of material inertia on the energy absorbed to the initiation of cleavage cracking.

The finite element method for localized failure analysis previously developed in collaboration with Professor M. Ortiz of Brown University was extended, in continued joint work with Professor Ortiz, to incorporate finite deformation effects and rate dependent material response. This method involves the use of additional shape functions that closely reproduce the localized deformation patterns. The additional degrees of freedom introduced are eliminated at the element level by static condensation. In fact, all calculations involving the additional degrees of freedom are carried out at the element level. One of the most surprising, and potentially most significant, outcomes of the numerical calculations carried out illustrating the methodology was the relative insensitivity of the finite deformation results to the initial orientation of the enhanced modes. This, in part at least, appeared to be due to accounting for finite deformations, which permitted the current orientation of the enhanced mode to evolve with the deformation history. This enhanced element approach can be used in conjunction with a broad range of constitutive descriptions and is applicable to a wide variety of solution procedures and finite elements in both two and three dimensions.

Research plans for the coming year are to work on extending the computational capability for localization and failure using microstructurally based constitutive relations to fully three dimensional situations and to continue to explore dynamic effects. Plans also include studies of effects of non-uniformity of distribution of second phases on plastic response and on failure.

Alan Needleman

Alan Needleman
Professor of Engineering

List of Publications/Reports/Presentations

1. Papers Published in Refereed Journals:

S.R. Nutt and A. Needleman, "Void Nucleation at Fiber Ends in Al-SiC Composites," *Scripta Metallurgica*, **21**, 705-710, 1987.

R. Becker, "The Effect of Porosity Distribution on Failure," *Journal of the Mechanics and Physics of Solids*, in press.

2. Technical Reports:

V. Tvergaard and A. Needleman, "Temperature and Rate Dependence of Charpy V-Notch Energies for a High Nitrogen Steel," submitted for publication.

A. Nacar, A. Needleman and M. Ortiz, "A Finite Element Method for Analyzing Localization in Rate Dependent Solids at Finite Strains," submitted for publication.

R. Becker, A. Needleman, O. Richmond and V. Tvergaard, "Void Growth and Failure in Notched Bars," *Journal of the Mechanics and Physics of Solids*, accepted for publication.

R. Becker, A. Needleman, S. Suresh, V. Tvergaard and A.K. Vasudevan, "An Analysis of Ductile Failure by Grain Boundary Void Growth," submitted for publication.

3. Presentations:

a. *Invited*:

A. Needleman, Winter Annual Meeting, ASME, Anaheim California, December 1986.

A. Needleman, Workshop on Strain Localization, University of Minnesota Institute for Mathematics and its Applications, Minneapolis, Minnesota, February 1987.

A. Needleman, CNRS Colloquium on **Mechanisms and Mechanics of Plasticity**, Aussois, France, April 1987.

A. Needleman, Summer Applied Mechanics Meeting, ASME, Cincinnati, Ohio, June 1987.

A. Needleman, 34th Army Sagamore Materials Conference, Lake George, New York, August 1987.

b. *Contributed*:

R. Becker and A. Needleman, Winter Annual Meeting, ASME, Anaheim California, December 1986.

A. Needleman, American Physical Society Meeting, New York, New York, March 1987.

List of Honors/Awards

none

Publications/Patents/Presentations/Honors

Papers submitted to refereed journals (and not yet published): 4

Papers published in refereed journals: 2

Books (and sections thereof) submitted for publication: 0

Books (and sections thereof) published: 0

Patents filed: 0

Patents granted: 0

Invited presentations at topical or scientific/technical society conferences: 5

Contributed presentations at topical or scientific/technical society conferences: 2

Honors/Awards/Prizes: 0

List of Participants

A. Needleman, Professor of Engineering
R. Becker, Graduate Student Research Assistant
A. Nacar, Graduate Student Research Assistant

Other Sponsored Research

Critical Conditions for Failure in Materials Subjected to High Rates of Loading	Army Research Office	$150,695	12/01/84-10/31/87
Micromechanical Modelling of Ductile Failure	National Science Foundation	$72,617	01/15/87-01/14/88
Plasticity and Fracture	National Science Foundation, Materials Group	$26,776	05/01/87-02/28/88

END
DATE
FILMED
MARCH
1988
DTIC