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DAMAGE ANALYSIS AND FUNDAMENTAL STUDIES FOR FUSION REACTOR MATERIALS DEVELOPMENT

Submitted by

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1. TECHNICAL PROGRESS SUMMARY FOR THE PERIOD 3/1/92-1/1/93

During this period work has encompassed: a) development of electropotential drop techniques to monitor the growth of cracks in steel specimens for a variety of specimen geometries; b) micromechanical modeling of fracture using finite element calculations of crack and notch-tip stress and strain fields; 3) examining helium effects on radiation damage in austenitic and ferritic stainless steels; 4) analysis of the degradation of the mechanical properties of austenitic stainless steels for the purpose of assessing the feasibility of using these steels in ITER; 5) development of an integrated approach to integrity assessment; and 6) development of advanced methods of measuring fracture properties.

a. Potential Drop Techniques

The work on electropotential drop techniques is a continuation of efforts to develop a data base from a variety of fracture specimen geometries to support the development of failure criteria for thin-walled structures containing part-through surface cracks. We have previously developed procedures for monitoring the evolution of cracks in miniaturized compact tension (CT) geometries. During the last work period we helped develop that capability at ORNL (with A. Rowcliffe and D. Alexander) in order to perform single-miniaturized specimen fracture toughness tests on ferritic and austenitic steels irradiated in HFIR. We have also continued to develop techniques for monitoring the growth of part-through cracks. This work is being carried out by a PhD candidate Mat Enmark. An experimental calibration between potential drop and crack size and shape has been developed and successfully used to assess surface crack growth in HT-9. The potential fields in a specimen containing a semi-elliptical crack have also been modeled using finite element techniques. The agreement between finite element predictions and empirical calibrations is excellent. Finally, the experimental and FEM studies are being extended center crack panels. The wide array of specimen geometries (three-point bend/compact tension, center-cracked panels, and surface-cracked panels), including a variety of crack depth to specimen width variations, will provide a reliable basis to predict failure conditions in complex fusion structures.

b. Micromechanics Modeling of Fracture

The work on combining micromechanical models of fracture with finite element analyses of crack tip stress fields is also part of the broader effort to develop: a) miniaturized testing procedures; b) reliable failure criteria; and c) better understanding of fracture mechanisms in steels to guide the design of alloys with improved resistance to radiation-induced changes in the temperature delineating ductile from brittle cleavage fracture. Most of the effort has been assessing the effects of: a) deviations from small scale yielding fields (ssy) on cleavage fracture toughness; b) large deformation crack blunting; c) statistical factors; d) microstructural heterogeneity and e) low strain constitutive behavior. The modeling has also been extended to evaluating deviations from ssy fields on ductile fracture. This effort has been supported by B. L.Chao, who is a post doctoral research engineer.

Further, the micromechanics models, including finite element studies, have recently been applied to blunt notch Charpy geometries. The objectives are to: a) better establish the relationship, if any, between Charpy parameters and fracture toughness; and b) to rigorously assess the effects of specimen miniaturization. Considerable progress has been achieved in addressing the latter issue. As long as plane strain conditions are maintained (certainly a valid assumption for fully brittle cleavage fracture) and cleavage is simply controlled by a maximum stress criteria (as often presumed), the behavior of full and subsized Charpy specimens should be (self) similar when normalized by specimen volume. This is also the case for ductile fracture, although this fracture mode is more complex and would be more likely to be affected by the loss of lateral plane strain constraint. However, if statistical factors impose a local stressed volume criteria (e.g., if cleavage requires a stress greater than some minimum value in a minimum volume of material) three effects are implied in small versus large specimens: a) temperatures characterizing the elastic fracture transition (fracture just prior to general yield) temperatures are lower; b) the transition regime between brittle and fully ductile fracture is narrower; and c) transition temperature shifts are smaller. These predictions are all consistent with observation, suggesting that statistical and stress-state effects are significant on the size scale of standard Charpy specimens and below. These concepts imply that universal energy scaling relations do **not** in fact exist. Moreover, whatever their size, CVN tests in and of themselves do not provide fundamental material properties. However, subsized specimens can be used to measure fundamental properties such as dynamic yield stress and statistical cleavage fracture criteria, and to test concepts for use in developing models of fracture.

c. Helium Effects in Austenitic and Ferritic Steels

Post irradiation characterization of the ORNL/UCSB/PNL isotope tailored alloys (^{58}Ni, ^{59}Ni, and ^{60}Ni isotopes) irradiated in the High Flux Isotope Reactor (HFIR) has been delayed. The objective of these experiments is to carry out single variable studies of the effects of He/dpa ratio in austenitic and ferritic steels. As a consequence of this delay, we have begun examining a series of alloys previously irradiated in the MOTA also aimed at studying the effects of helium effects on swelling and mechanical properties. The irradiations were carried out at 400, 500, and 600°C to exposures of 15, 30, 60 and 105 dpa. A series of austenitic and HT-9 TEM discs were pre-implanted with helium at the Davis cyclotron. A subset of these specimens was aged at 800°C for 1h following implantation. Thus the specimens have a pre-irradiation distribution of helium ranging from isolated gas atoms to small bubbles. The post-irradiation examination are now being carried out by one our students (Mychailo Toloczko) in residence at PNL (partly supported by the NORCUS). The PIE includes: densitometry, TEM, and shear punch testing. In the last six months the specimens have been assembled, cleaned and sorted and a shear punch test fixture has been installed at PNL. Actual testing has recently begun. Frank Garner, Dave Gelles and Peggy Hamilton are assisting with this project.

d. Austenitic Stainless Steel Properties

We have continued to analyze and evaluate the data on the properties (i.e., tensile and fracture toughness) and microstructures of irradiated 300-series stainless steels for irradiation and test temperatures pertinent to the ITER design parameters. This assessment has been used as a basis to estimate the viability of using austenitics in the ITER structure and to identify critical ITER-related research and data base requirements. These studies have led us to believe that the use of austenitic stainless steel for the ITER structure will present a major engineering challenge.

Consideration of ductile fracture models in the context of the irradiated 300-series steel data base suggests that fracture may change from a microvoid-coalescence dominated process in the unirradiated material, to a microvoid-shear linkage process at moderate exposures, to a mechanism dominated by deformation and failure in a concentrated process zone in highly irradiated material. Under the latter conditions, the loss of uniform ductility and flow localization promoted by irradiation may lead to extensive subcritical crack growth in the absence of significant matrix plasticity surrounding the process zone. Cold-worked steels may be more resistant to the onset of this type of fracture process than alloys in the solution annealed condition.

e. New Approaches To Characterizing Fracture of Flawed Fusion Structures

Standard elastic and elastic plastic fracture mechanics approaches to characterizing the integrity of flawed fusion structures are clearly inadequate. The minimal information needed to accurately fracture conditions include:

1. The relevant set of material properties that control fracture.

2. Analytical techniques to apply the property data to complex structures.

The property measurements must include the effects of irradiation, hence, implicitly require the use of what are considered 'small' specimens from a standard pressure vessel and boiler code perspective. In the latter case, sufficiently large specimens and relatively simple analytical procedures produce generally conservative, but nevertheless useful measures of safety margins. In contrast the varying size scales, complex loading and significance of both primary and secondary stress encountered in fusion structures will require much more sophisticated approaches. Indeed, the most direct approach in this case would be to provide designers with procedures and an associated data base that would permit them to evaluate structural design widows and safety margins based on the load-displacement capacity of prototypical flawed structural subelements. The analytical procedures/material data base could be readily incorporated as subroutines in elastic or inelastic structural design codes.

We have proposed the following integrated approach to fracture assessment:

1. Generate a coarse matrix of FEM simulations of crack tip (stress and strain) fields in prototypical subelement geometries.

2. Develop and validate models of local fracture properties, viz., the (tip) stress-strain field conditions leading to crack extension.

3. Develop and validate miniaturized specimens to measure the fracture properties.

4. Develop a data base on the failure properties for irradiated alloys.

5. Catalog the computational results and develop easily applicable interpolation procedures (i.e., using T- and Q-stresses) to interpolate the analytical results to arbitrary loading conditions.

6. Integrate the data base and analytical procedure in a user-friendly package for use by designers.

f. Advanced Methods of Measuring Local Fracture Properties

During this work period research has initiated on a tremendously exciting approach to developing local fracture models and measuring local fracture properties. The main focus of this effort is to develop and apply the emerging technique of confocal microscopy (CM). This work is being carried out by PhD candidate Kurt Edsinger. The objective of this application of CM is to provide three-dimensional fractographic information by optical sectioning. There are a number of approaches to CM. The system we are developing provides real-time images with a submicron vertical resolution. While simple in principle, CM offers a number of technical challenges, particularly with regard to specimen preparation and the information processing required in three dimensional reconstruction. We have acquired a CM and developed procedures for data filtering, smoothing and reconstruction. The instrument is currently being modifies to permit sampling of large areas (mm's x mm's).

By appropriate application of the three dimensional fractographic information it is possible to reconstruct the sequence of events leading to both initial and continued crack extension. Scanning confocal microscopy reconstruction (CMR) is accomplished by evaluating the local evolution of material separation between precisely aligned conjugate fracture surfaces. Approximate approaches to CMR which neglect the in plane-off surface deformations have already been developed by Kobiashi and co-workers. This work will couple the observations with finite element models to mitigate the effects of these approximations.

The CMR provides a wealth of information on both fracture mechanism and local fracture properties. For example this technique immediately provides crack tip opening displacement measurements that are a direct measure of both initiation and resistance curve toughness. For cleavage fracture CMR provides information on: cleavage crack initiation sites and frequencies; statistical critical stress-volume functions; microcrack, microcrack arrest, quasi-cleavage shear step distributions; crack paths and microstructure-event correlations. More significantly CMR can provide a detailed description of the process zone mechanisms leading to cleavage. Similarly for ductile fracture, CMR provides information on: microvoid nucleation sites and strains; microvoid growth rates and interactions; coalescence strains; microstructure-event correlations; and fracture paths. CMR may provide even greater fundamental insight on mixed mode fracture mechanisms and properties.

4. PUBLICATIONS DURING LAST PERIOD

1. Lucas, G. E., Odette, G. R., Chao, B. L., "On Size and Geometry Effects on the Brittle Fracture of Ferritic and Tempered Martensitic Steels," *J. Nucl. Mater.* **191-194** (1992) 827-830.

2. Enmark, M., Lucas, G., Odette, G. R., "An Electric Potential Drop Technique for Characterizing Part-Through Surface Cracks," *J. Nucl. Mater.* **191-194** (1992) 1038-1041.

3. Odette, G. R. and Lucas, G. E., "Deformation and Fracture in Irradiated Austenitic Stainless Steels," *J. Nucl. Mater.* **191-194** (1992) 50-57. (invited)

4. Lucas, G. E. and Odette, G. R., "Why SA316 Stainless Steel Might Not Work for the ITER Structure," *Trans ANS* , **65** (1992) 190-191.

5. Enmark, M., Lucas, G., Odette, G. R., "Finite Element Calibration of an Electropotential Drop Technique for Characterizing Part-Through Surface Cracks," *Trans ANS*, **66** (1992) 199-200.

6. Lucas, G. E., "The Evolution of Mechanical Property Changes in Irradiated Austenitic Stainless Steels," submitted to *J. Nuc. Mater.*

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