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ON

DAMAGE ANALYSIS AND FUNDAMENTAL STUDIES FOR
FUSION REACTOR MATERIALS DEVELOPMENT

For the Period

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INTRODUCTION

The philosophy of the program at the University of California Santa Barbara has been to develop a fundamental understanding of both the basic damage processes and microstructural evolution that take place in a material during neutron irradiation and the consequent dimensional and mechanical property changes. This fundamental understanding can be used in conjunction with empirical data obtained from a variety of irradiation facilities to develop physically-based models of neutron irradiation effects in structural materials. The models in turn can be used to guide alloy development and to help extrapolate the irradiation data base (expected to be largely fission reactor based) to the fusion reactor regime. This philosophy is consistent with that of the national and international programs for developing structural materials for fusion reactors.

SUMMARY OF WORK

During this period work has encompassed: 1) 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; 2) examining helium effects on radiation damage in austenitic and ferritic stainless steels; 3) development and application of electropotential drop techniques to monitor the growth of cracks in steel specimens for a variety of specimen geometries; 4) development of advanced methods of measuring fracture properties; 5) combining micromechanical modeling of fracture with finite element calculations of crack and notch-tip stress and strain fields to predict failure; 6) developing a data base on flow and fracture properties of ferritic steels. Each of these activities is described in more detail below and in greater detail in the attached publications.

1) Austenitic Stainless Steel Properties

We have analyzed and evaluated the data on the mechanical properties (i.e., tensile, fracture toughness, fatigue) 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. Fatigue life and IASCC are also major considerations in this temperature and dose regime.

2) Helium Effects in Austenitic and Ferritic Steels

We have participated in two experiments to evaluate the effect of helium on the microstructure, dimensional stability and mechanical properties of austenitic and ferritic stainless steels. The first has been a joint ORNL/UCSB/PNL experiment on isotope tailored alloys (^{58}Ni , ^{59}Ni , and ^{60}Ni isotopes) irradiated in the High Flux Isotope Reactor (HFIR). The objective of these experiments is to carry out single variable

studies of the effects of He/dpa ratio in austenitic and ferritic steels. The irradiations were delayed during much of this work period because of the HFIR startup problems. Densitometry has now been conducted on several sets of irradiated alloys, and our participation in other post-irradiation examinations will await future work.

In addition we have been 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 stainless steel 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 had a pre-irradiation distribution of helium ranging from isolated gas atoms to small bubbles. Many of these specimens were rendered unusable by temperature over-transients during the MOTA irradiations. Several sets at low and high dose, however, were recovered. The post-irradiation examination has been carried out by one of our students (Mychailo Toloczko) in residence at PNL (partly supported by the NORCUS) as well as at UCSB. The PIE includes: densitometry, TEM, and shear punch testing. Frank Garner, Dave Gelles and Peggy Hamilton have been assisting with this project. To date only the high exposure specimens (34-50 dpa) at all three irradiation temperatures have been examined. Microstructures and mechanical properties are consistent with the data trends for both ferritic and austenitic steels. In the austenitic steels, the effects of pre-implanted helium (nominally 100 appm on average) appear to be modest at these high doses.

3) Potential Drop Techniques

The work on electropotential drop techniques is a part of an overall effort 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 developed procedures for monitoring the evolution of cracks in miniaturized compact tension (CT) geometries, and 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 and apply techniques for monitoring the growth of part-through cracks. This work is being carried out by a PhD candidate Matt 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 specimens containing semi-elliptical cracks 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 have been extended to center-cracked panels. Application of these techniques to both surface cracked and center-cracked panels is now in progress. 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.

4) Advanced Methods of Measuring Local Fracture Properties

During this work period research was initiated on a tremendously exciting approach to developing local fracture models and measuring local fracture properties. The main focus of this effort has been to develop and apply the emerging technique of confocal microscopy (CM). This work was carried out by PhD candidate Kurt Edsinger. The objective of this application of CM is to provide quantitative, three-dimensional, fractographic information by optical sectioning. The system we have developed provides real-time images with resolution in all three dimensions of about

0.5 μ m. The work has included the installation of a CM, the design and fabrication of computer controlled x-y-z stages, and the development of procedures for data filtering, smoothing and reconstruction.

The resulting CM micrographs have been used to reconstruct the sequence of events leading to both initial and continued crack extension by evaluating computationally the local evolution of material separation between precisely aligned conjugate fracture surfaces. This requires coupling the conjugate, CM fracture maps with the appropriate displacement fields determined by finite element models for the specimen geometry and material constitutive law of interest.

The CM/fracture reconstruction (FR) provides a wealth of information on both fracture mechanism and local fracture properties. For example this technique provides crack tip opening displacement measurements that are a direct measure of both initiation and resistance curve toughness. For cleavage and quasi-cleavage fracture CM/FR 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 CM/FR can provide a detailed description of the process zone mechanisms leading to cleavage. Similarly for ductile fracture, CM/FR provides information on: microvoid nucleation sites and strains; microvoid growth rates and interactions; coalescence strains; microstructure-event correlations; and fracture paths. CM/FR can provide even greater fundamental insight on mixed mode fracture mechanisms and properties.

5) Micromechanics Modeling of Fracture

We have been developing a general approach to predicting fracture by combining a local crack tip failure criteria based on the micromechanics of the fracture process occurring there with an accurate description of crack tip stress/strain fields for a

crack and component geometry of interest using finite element methods. The approach relies strongly on the use of CM/FR analysis to understand the micromechanisms of fracture and to quantify critical fracture parameters. While the work has largely focused on the quasi-cleavage fracture of tempered martensitic stainless steels it has considerable potential for much more general application.

CM/FR analysis has shown that quasi-cleavage fracture in HT-9 proceeds by the early onset of stable, multiple microcracking ahead of the crack tip followed by rapid coalescence of the microcrack/tear ridge regions into a single or few large process zone cracks (PZC) extending over many prior austenite grains; these PZC's quickly grow to a point of instability, and the crack propagates catastrophically. This quasi-cleavage (QC) fracture mechanism can be modeled in terms of the stable growth of a bridged PZC up to a point of instability, and the instability criteria can be cast in the form of a critical area ahead of the crack tip A^* being stressed in the direction normal to the crack plane above a critical stress σ^* .

The A^* - σ^* criteria can be assessed by combining a large scale bridging analysis with CM/FR data or by combining finite element analysis with mechanical property data on a relatively few specimens. The A^* - σ^* criteria can in turn be combined with finite element analyses of specimen/crack/notch geometries of interest and a known constitutive law to predict fracture. For instance, predictions of fracture toughness (K_{IC}) and absorbed energy (Charpy-V-notch) as a function of test temperature are in excellent agreement with experimental data; and the calculated behavior accurately shows the effects of specimen size (CVN vs MVCN) and the deviation from small scale yielding as the crack to specimen width ratio decreases.

Analogous procedures can be developed and applied to predicting critical conditions for ductile fracture initiation by invoking critical strain criteria. Indeed, more sophisticated micromechanical models of fracture can be applied, such as statistical

models of cleavage or microvoid growth and coalescence, within this framework. Hence, the opportunity exists to apply this approach to the range of fracture mechanisms operating in materials being considered for structural applications in fusion machines (austenitic stainless steels, ferritic steels, vanadium alloys...), and the framework promises a rather robust approach to utilizing small specimen data to predict fracture in fusion-like structures.

6) Data Base on Ferritic Steels

We have been developing a data base on flow and fracture properties of ferritic steels. This includes both unirradiated and irradiated data on HT-9 and 9Cr-1Mo steels gleaned from the literature as well as tensile and fracture properties on unirradiated HT-9 that we have developed. In addition we have initiated a data base on unirradiated properties of the F82H/IEA steels that we have been testing in our laboratory.

A summary of papers and reports which have been generated in these areas during the work period is provided in Appendix I. Copies of the papers are included as attachments.

APPENDIX I

PUBLICATIONS GENERATED DURING THE WORK PERIOD

1. Odette, G. R., Chao, B. L., Lucas, G. E., "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," *J. Nucl. Mater.* **206** (1993) 287-305. (invited)
7. Pawel, J. E., Alexander, D. J., Grossbeck, M. L., Longest, A. W., Rowcliffe, A. F., Lucas, G. E., Jitsukawa, S., Hishinuma, A., Shiba, K., "Fracture Toughness of Candidate Materials for ITER First Wall, Blanket, and Shield Structures," *J. Nucl. Mater.* **212-215** (1994) 442-448.
8. Lucas, G. E., "Effects of Radiation on the Mechanical Properties of Structural Materials," *J. Nucl. Mater.*, **216** (1994) 322-325.
9. Odette, G. R., "On the Ductile to Brittle Transition in Martensitic Stainless Steels - Mechanisms, Models and Structural Implications," *J. Nucl. Mater.*, **212-215** (1994) 45-53.

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