Phase Two Technical Report

The Effect of Localized Flow on Fracture of Reactor Components

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I. Program Perspective and Goals

This program is an experimental and computational modeling research effort to understand and characterize the response of reactor structural materials to irradiation exposure leading to plastic instability during deformation resulting in very low resistance to fracture. It addresses the problem with a coordinated, multi-scale approach which bridges materials response at the microstructural level to the structural performance of large-scale components. This work provides basic insight to handle a major reactor structural materials performance effect due to irradiation exposure. This is a significant issue in current and future reactor materials selection and application since it is now clear that all reactor structural materials, regardless of their crystal type, can be significantly embrittled under certain irradiation conditions. This has real consequences for reactor safety due to structural integrity of components and is a significant issue in the selection of materials and operating conditions for new reactor and reactor component designs. This program will identify the microstructural conditions that lead to flow localization, and will take the significant additional step to develop materials deformation models to capture the salient deformation features. This report describes the work accomplished in the past year during Phase II of the program. (A report covering work in Phase I was submitted on October 5, 2003.)

II. Introduction

316L and 304L austenitic stainless steels are widely used as core internal and structural component materials in nuclear applications. Mechanical properties changes due to the irradiation environment, such as loss of material tensile ductility, have been a major concern for these materials. In this study, tensile test data for 316L and 304L stainless steels irradiated in fission reactor neutron flux or spallation neutron and proton fluxes with doses up to 12 dpa at irradiation temperatures from 30 to 400ºC and tested at the temperature range of room temperature to 400ºC have been analyzed and compared to properties of unirradiated 316L SS. There is a strong linear relationship between the yield strength and the uniform elongation. For each material and test temperature examined, the true stress at the onset of necking remained at nearly constant regardless of irradiation dose. This “critical stress” for the onset of plastic instability seems to be a property of materials and insensitive to radiation conditions. It is also found that the critical stress has a strong dependence on the tensile test temperature. Plastic strain hardening behavior is a linear function of true stress at larger plastic strain levels. Initial investigations of the deformation microstructure show that slip band formation and interaction are a critical factor controlling the strain hardening and plastic instability behavior.

III. Analysis

III.1 Tensile response of 316L SS as a function of test temperature

In order to examine the behavior of true stress at the onset of necking and its temperature dependence for 316L stainless steel, high temperature tensile tests were performed in this study for unirradiated 316L stainless steel from 20 to 600ºC in at the Advance Materials Testing and Evaluation Laboratory (AMTEL) in Talbot Laboratory at University of Illinois at Urbana-Champaign. The true stress- strain curves for this study are shown in Figure 1. More details about the temperature dependence of the tensile response will be discussed later in this study.

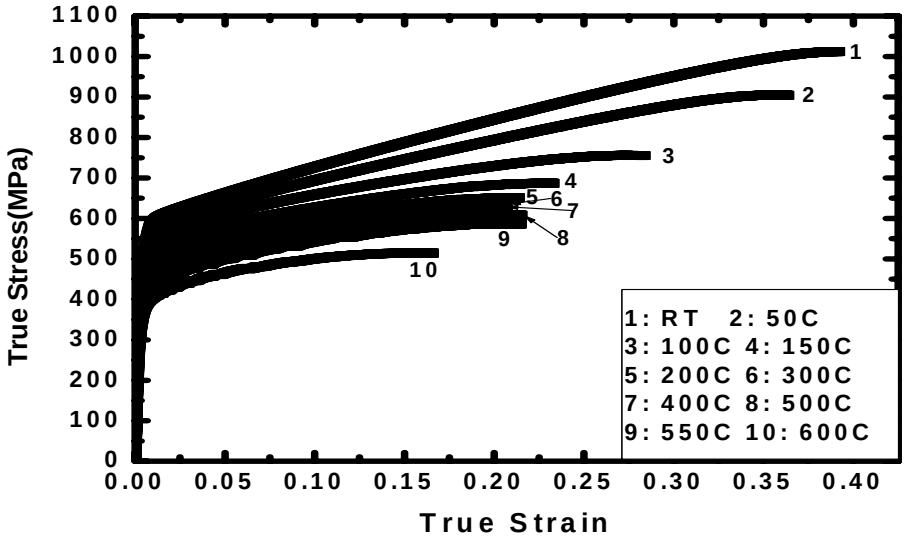


Figure 1 True stress-strain relationship for unirradiated 316L stainless steel tested at temperature from 20 to 600ºC

III.2. Correlations of Yield Strength and Uniform Elongation

It is useful to examine the true stress – true strain tensile curves to better understand the actual stress states at the point of necking. Figure 2 shows the true stress-true strain curve for EC316LN tested at 20ºC. The true stress at the onset of necking is nearly constant regardless the radiation level. This true stress level for onset of necking has been termed the "critical stress" in our work, and seems to be independent of irradiation exposure. For the case of EC316LN at 20 ºC, the radiation level ranges from unirradiated to 10.7dpa while the critical stress is consistently around 950MPa. The same effect can be seen from tensile data at 50 and 164ºC in Figures 3 and 4. From the results presented above, it appears that the true stress at the onset of necking is a material property and not a function of radiation-induced defect microstructure, dislocation multiplication mechanisms or strain hardening behavior. The critical stress is reasonably insensitive to irradiation conditions.

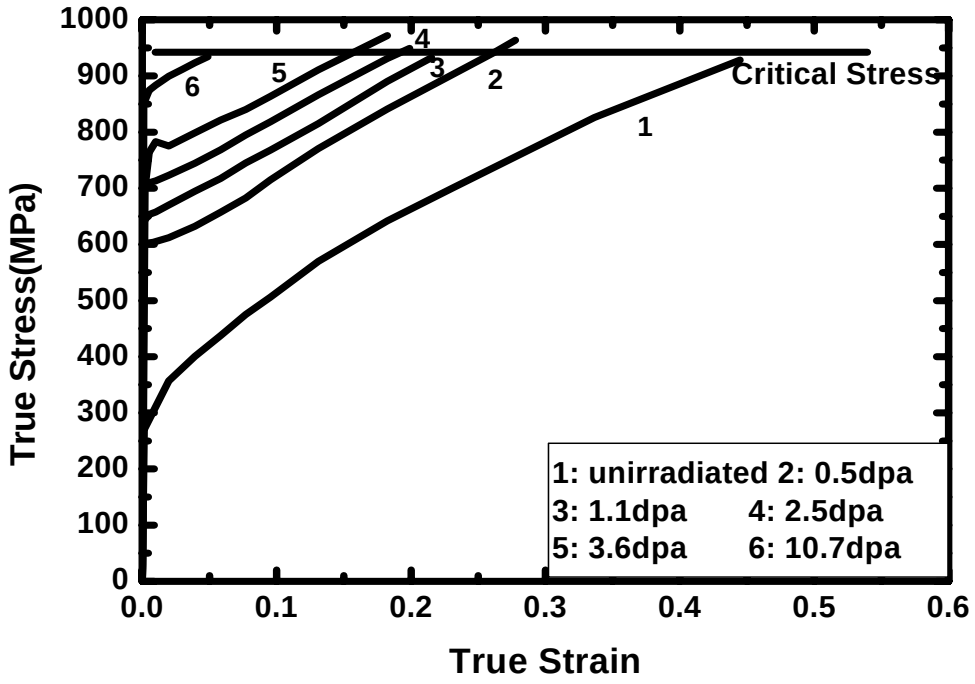


Figure 2 The true stress-strain tensile curves are shown for EC316LNSS tested at room temperature [1]

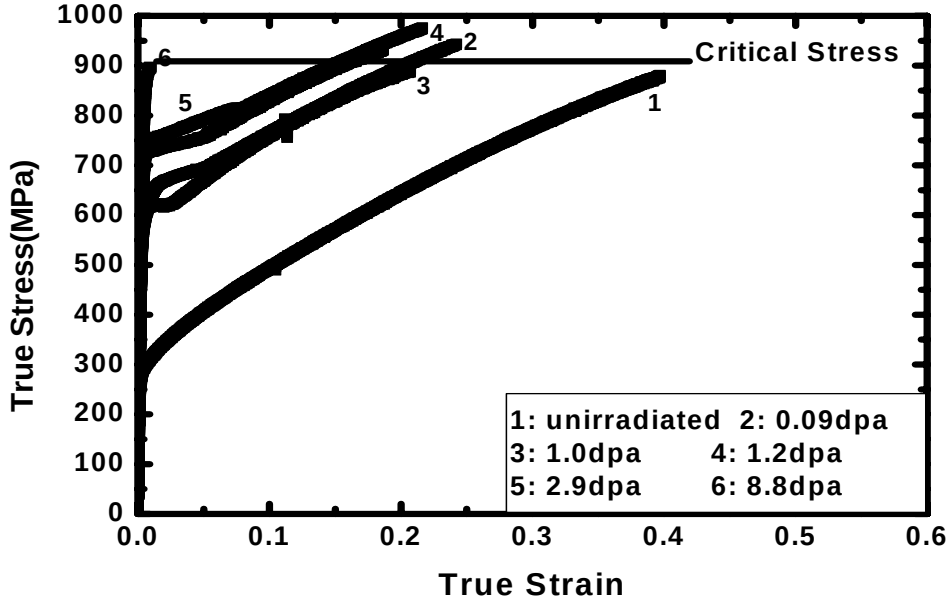


Figure 3 The true stress-strain tensile curves are shown for 316L tested at 50ºC [2]

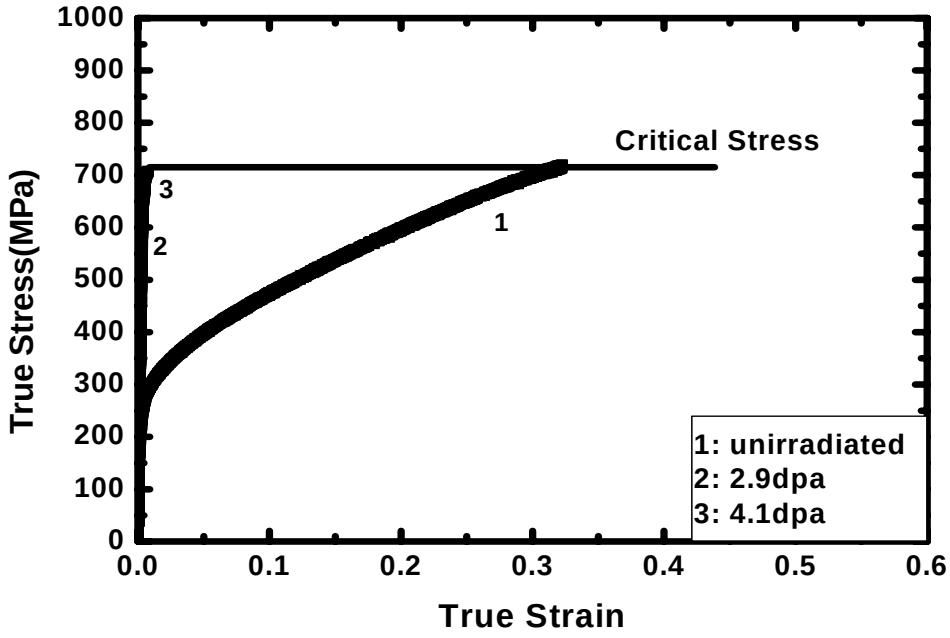


Figure 4 The true stress-strain tensile curves are shown for 316L tested at 164ºC [2]

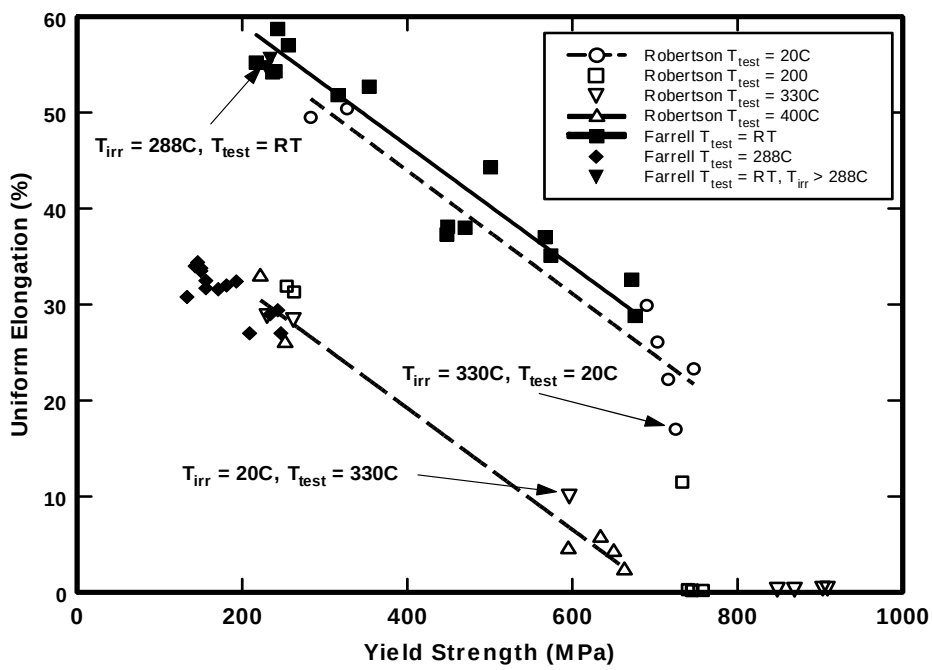
It can be concluded that there is the strong correlation between material yield stress and uniform elongation, which is independent of irradiation condition. In all of the preceding cases, there is also a critical stress level above which uniform elongation stops and necking starts. This level seems to be independent of irradiation condition for the materials examined here. The intersection of the yield strength – uniform elongation trend curves with the yield strength axis defines a critical stress at which flow localization takes place upon yielding. This point is consistent with the true stress level at the onset of necking for all tensile curves regardless of radiation damage level. In the current cases, the full tensile curves are available to examine the precise strain hardening behavior leading to the end of uniform tensile elongation. In many cases, the full tensile curves are not available for analysis. In the absence of full tensile curve data it is possible to develop a reasonable estimate of the critical stress level using only the yield strength and uniform elongation data. Figure 5 shows the correlation between uniform elongation and yield stress for 316L and 304L stainless steel. The very strong linear relationship between

uniform elongation and yield strength suggests a simple model for predicting uniform elongation or plastic instability based on materials yield strength. The level of uniform elongation, ε_u, can be predicted by equations of the form

$$\varepsilon_u = \varepsilon_u^0 - m \bullet \sigma_{ys} \qquad \text{for } \sigma < \sigma_{crit}$$

$$\varepsilon_u \sim 0 \qquad \text{for } \sigma \geq \sigma_{crit}$$

where ε_u^0 is the intercept on the uniform elongation axis and *m* is the slope of the trend line. This approach is limited more by the variation in material yield strength than in the critical stress.



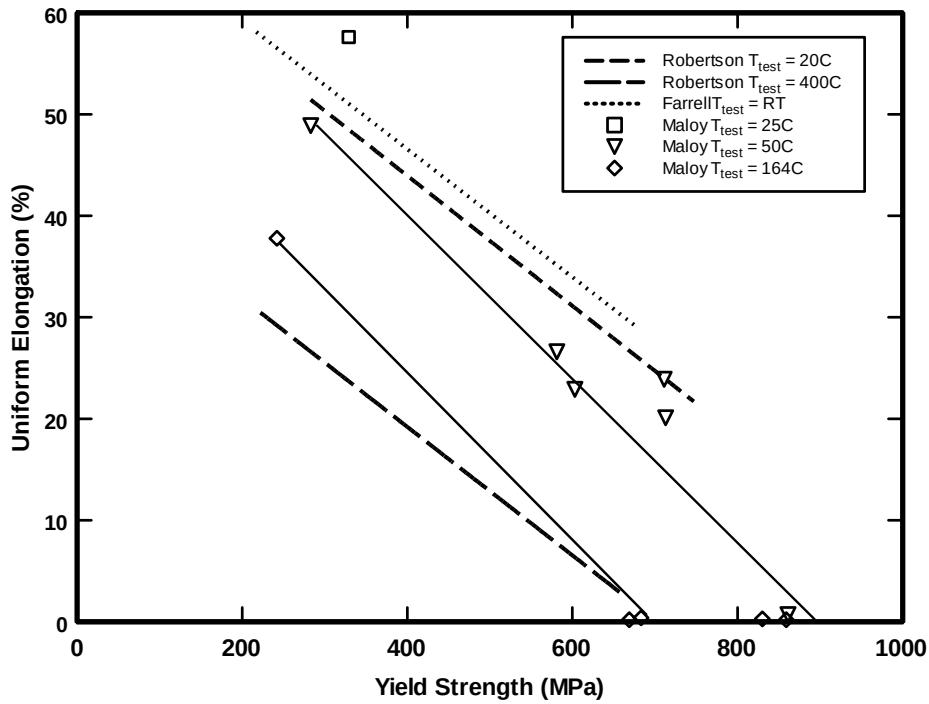
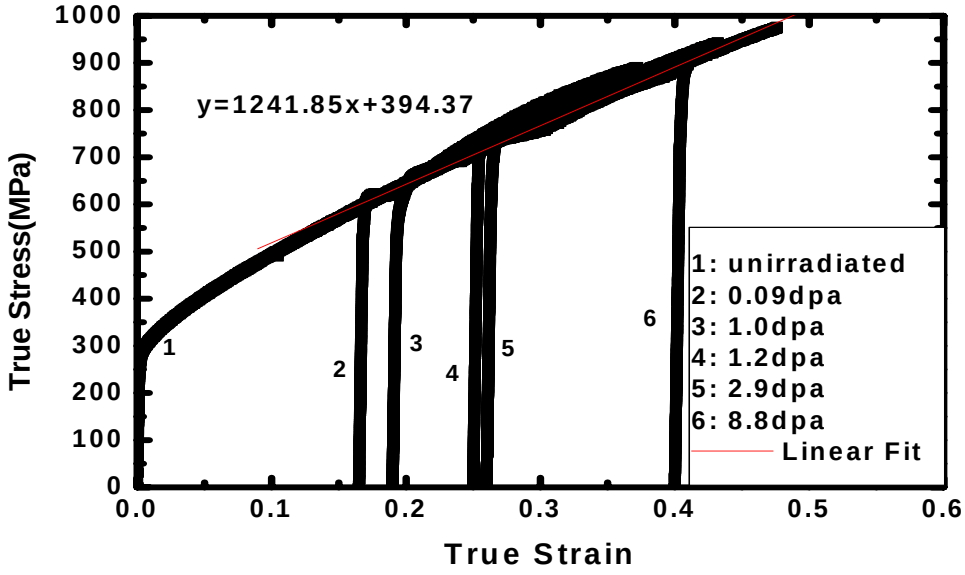
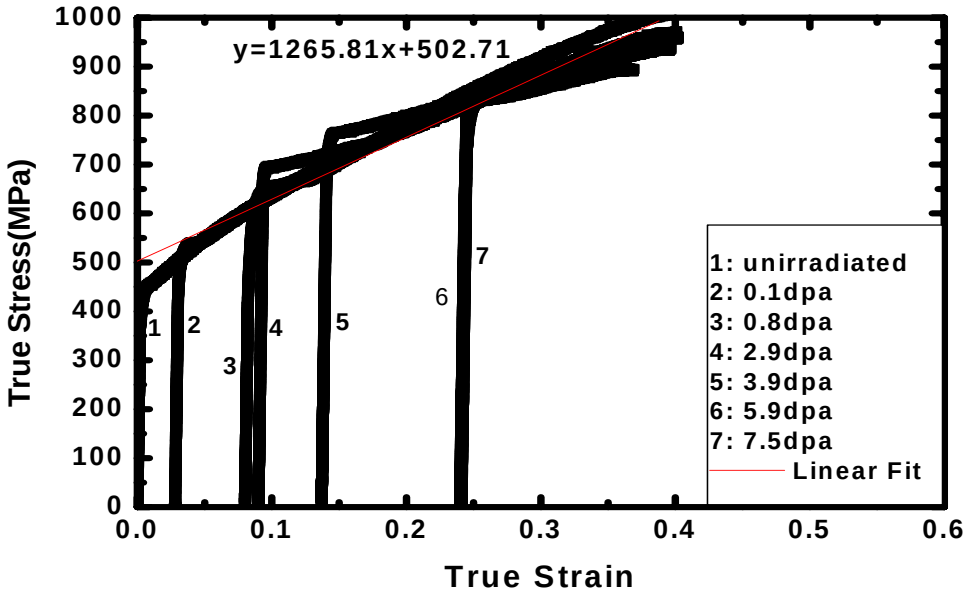


Figure 5 The relationship between uniform elongation and yield strength for 316L stainless steel [3-5]

Byun and Farrell [1] proposed a plotting method so that the curves are shifted proportional to their increase in yield strength. This approach makes it more obvious that the final portions of the curves all exhibit essentially the same strain hardening behavior prior to necking. It is also notable that the last segments of the strain hardening curves are nearly linear. All these materials exhibit three stages to the tensile behavior: linear elastic deformation, post-yield strain hardening, and a final linear strain hardening portion leading to necking. In several cases, the irradiated material does not show the intermediate strain hardening behavior; rather elastic yield is followed by a direct linear hardening until necking. In the cases where there is no intermediate strain hardening phase, the values of the intercept are a good approximation of the material yield point. Figure 6 shows the curves for 304L and 316L.



(a)



(b)

Figure 6 The true stress-strain tensile curves are shown for (a) 316L SS tested at 50°C [2], and (b) 304 SS tested at 50°C [2] with the curves shifted proportional to the irradiation-induced increases in yield strength. The fit to the linear strain hardening region is shown.

III.3. Temperature Dependence of the Critical Stress

A major concern with the use of austenitic stainless steel in irradiation environments is the strong drop of uniform elongation and critical stress with irradiation exposure between 150 and 400ºC. This drop is perplexing since the rate of irradiation hardening is reasonably similar at temperatures from room temperature to nearly 400ºC. Nevertheless, the loss of ductility is most extreme in the intermediate temperature range. A strong drop in uniform elongation is found between room temperature and 150ºC, and a reasonably flat plateau is found up to 400ºC.

Figure 7 indicates the strong temperature dependence of the critical stress in type 316 SS and the relatively moderate temperature dependence of the yield strength. The uniform elongations are shown as a function of test temperature and follow a trend which is similar to, but with somewhat less temperature dependence as, the critical stress. The band between the yield strength and the critical stress level indicates the amount of irradiation-induced hardening that the material can withstand before undergoing flow localization upon loading. It is clear that much higher hardening levels can be tolerated at room temperature than between 200 and 600ºC. While the current material has a somewhat higher yield than the other versions of 316 SS examined here, the strong temperature difference of the critical stress accounts for the observed low ductility in this alloy following irradiation between 150 and 400ºC. It is also noteworthy that the difference between the yield strength and the critical stress is nearly uniform in the temperature range between 150 and 400ºC, consistent with the observed plateau in the tendency for flow localization in this temperature range.

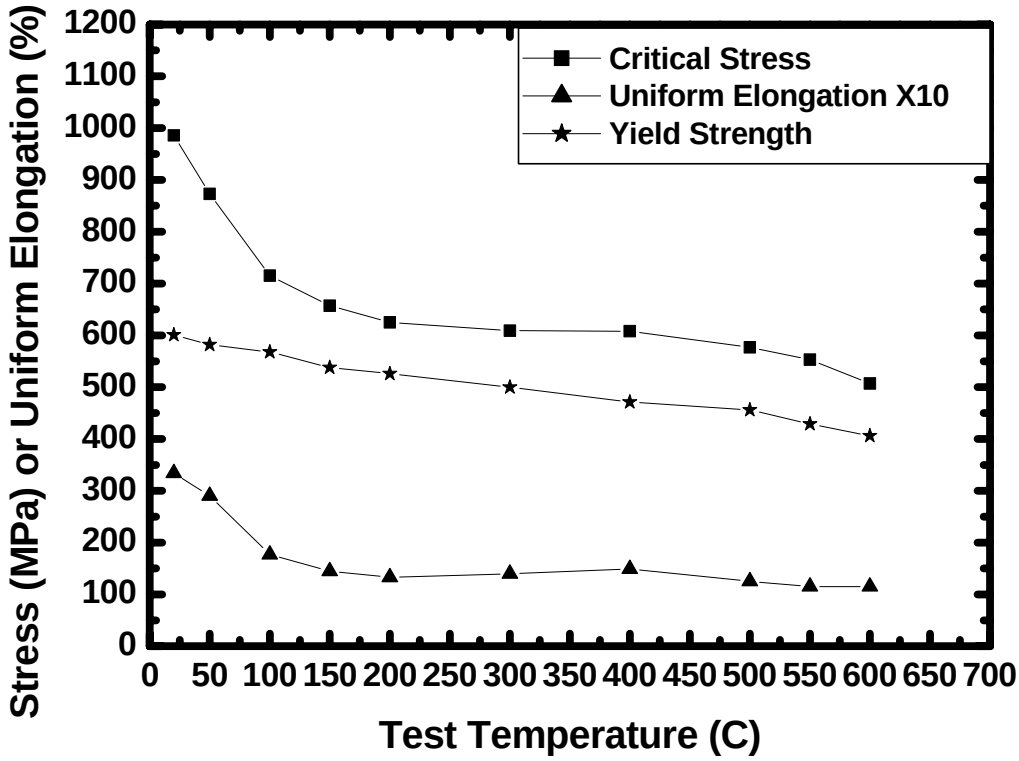
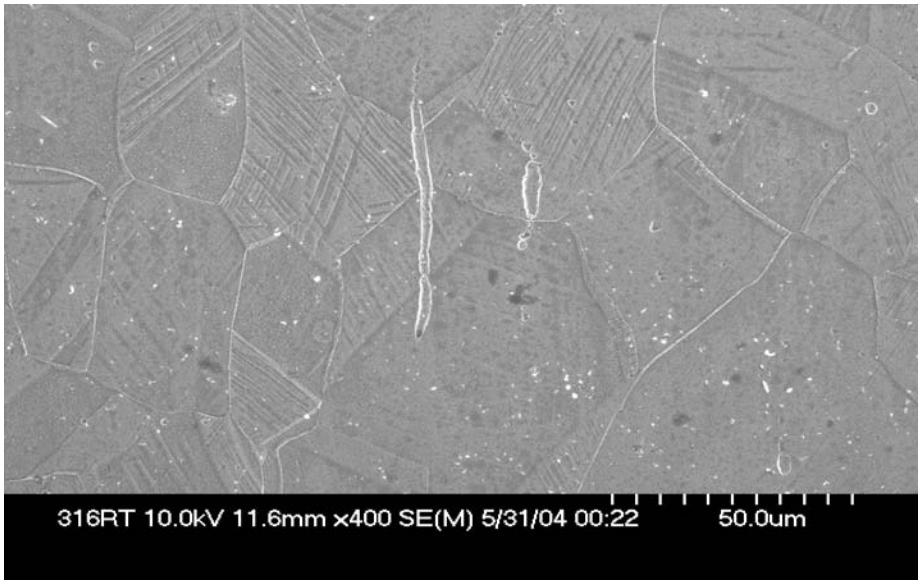


Figure 7 The critical stress for the onset of necking in 316 SS is shown as a function of temperature. The temperature dependence of yield strength and uniform elongation are also shown.

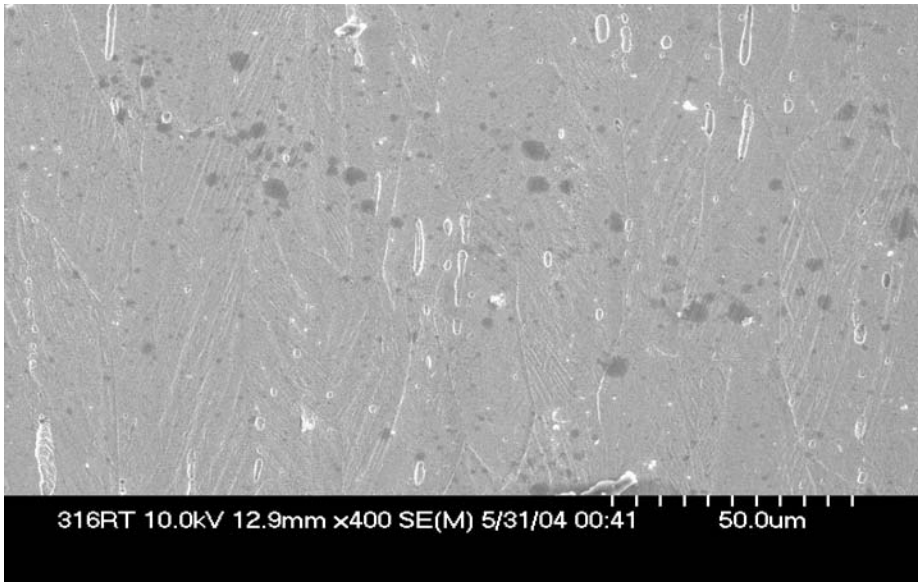
III.4. Materials Deformation Processes

The underlying materials flow processes which control the flow localization process has been a major point of research interest. Most work has concentrated on the processes which limit dislocation flow and result in highly localized deformation (slip) bands. The current results and other recent work [1], indicate that the latter stages of deformation are nearly the same regardless of the irradiation conditions for the metals and alloys considered here. This would indicate that the most important factor is the nearly linear strain hardening which takes place prior to necking. This process must be similar in all cases, regardless of irradiation state, and be highly dependent on a well-developed flow process. In order to better establish the controlling process, micrographs of 316L

deformed at room temperature were obtained in a section which had only undergone uniform elongation and one in a region which had started to neck. These two microstructures are compared in Figure 7 where it is evident that multiple slip bands have formed in both cases. The major difference is that the grains are equiaxed in the region prior to necking and are highly deformed and elongated in the necked region. This major change in grain shape must be due directly to the slip banding process. It is also apparent that the plasticity-induced voids are formed around particles and inclusions; rather than nucleating at highly deformed grain boundary sites. This supports a flow process which is controlled by slip band formation and deformation processes resulting in a hardening which eventually nucleates plasticity voids on available particles. This helps explain the rather systematic hardening processes in both unirradiated and irradiated material. The nature of the slip band formation and flow processes must also be the principle controlling mechanism in the temperature dependence of the critical stress. This issue is currently under continuing investigation.



(a)



(b)

Figure 8 SEM micrographs of 316L SS tensile specimen (a) outside of the necking area and (b) after necking occur. Note the slip bands and grain orientations.

IV. Summary of Major Findings

The tensile behavior of selected FCC metals, Ni, Au, Cu, 316L and 304L, was tested and analyzed in a temperature range from RT to 400ºC. The results are summarized as follows:

(1) For the FCC metals and alloys studied here, the yield stress increases while the uniform elongation decreases with irradiation exposure. The ultimate tensile strength is not affected by irradiation exposure.

(2) For the FCC metals and alloys studied here, there is a “critical stress” for the onset of necking. The value of this critical stress is reasonably insensitive to irradiation condition. The critical stress seems to be a material property and is a function of test temperature.

(3) There is a linear relationship between uniform elongation and yield stress. The intersection of linear trend line with the yield stress axis is defined as critical stress and coincides with the true stress to failure.

(4) The critical stress concept indicates that the onset of necking is controlled only by inherent materials properties and not the defect-dislocation interactions which affect the material yield strength.

(5) For the materials studied here, slip bands are found in the equiaxed grains in the region prior to necking and in the highly deformed grains in the necked region indicating that slip band formation is the major microstructure process controlling linear strain hardening and the onset of necking.

V. Phase III: Future Work

There are a number of interesting findings in the current work that require further clarification and research. Future efforts will be directed at the following:

1. Temperature dependence of critical stress and dependence on stacking fault energy or other materials parameters. Current work shows there is a strong temperature dependence of critical stress; future work should be applied to discover the parameters which cause this dependence, these parameters maybe include the stacking fault energy, Young's Modulus etc.

2. FEM analysis of necking and void formation. Some FEM and microstructure microscopy work has been performed and more work will be brought out in the future to model the necking process and to determine the relationship between void nucleation strain and spacing among inclusions to clarify the plasticity-induced void nucleation process that control the critical stress value. Slip band and grain deformation processes and plasticity induced void nucleate, growth and coalescence should also be studied in detail.

3. Relationship of the tensile properties to fracture toughness. Future work will be applied to discover the relationship between tensile properties and fracture toughness which is directly associated to materials necking and fracture mechanisms.

VI. Publications from this Project:

1. Xiao Pan, Xianglin Wu, Meimei Li and James F. Stubbins, “Modeling tensile response and flow localization effects in selected copper alloys,” J. Nucl. Mater., Vol 329-333PB (2004) pp 1088-1092.
2. Meimei Li and James F. Stubbins, “Room Temperature Creep-Fatigue Response of Selected Copper Alloys for High Heat Flux Applications,” J. Nucl. Mater., Vol 329-333PA (2004) pp 865-869.
3. Xianglin Wu, Xiao Pan, Meimei Li and James F. Stubbins, “Modeling tensile response and flow localization in 316SS after exposure to spallation and fission irradiation environments,” submitted to J. Nucl. Mater. (2003) for publication.
4. Meimei Li and James F. Stubbins “Fatigue Response and Life Prediction of Selected Reactor Materials,” Effects of Radiation on Materials: 21st International Symposium, ASTM STP 1447, M. L. Grossbeck, T. R. Allen, R. G. Lott, and A. S. Kumar, Eds., ASTM International, West Conshohocken, PA, 2004, in press
5. Meimei Li and James F. Stubbins “Evaluation of Irradiation Effect on Fatigue Performance of Copper Alloys for High Heat Flux Applications,” Journal of Fusion Science and Technology, 44 (1) (July 2003) 186-190.
6. Meimei Li and James F. Stubbins “Creep-Fatigue Behavior in High Strength Copper Alloys,” accepted for publication in Journal ASTM International (2004)
7. Xianglin Wu, Xiao Pan, Meimei Li and James F. Stubbins, “Flow Localization Processes in Austenitic Alloys,” submitted for publication in Journal ASTM International (2004)
8. Xianglin Wu, Xiao Pan, Meimei Li and James F. Stubbins, “Flow Localization in FCC Metals Subjected to Irradiation,” accepted for publication in ANS Transactions (Nov 2004)

VII. References

[1] T.S. Byun and K. Farrell, “Plastic instability in polycrystalline metals after low temperature irradiation,” Acta Mat. 52 (2004) 1597-1608.

[2] S. Maloy, MR James, G Willcutt, WF Sommer, M Sokolov, LL Snead, ML Hamilton, F Garner, “The mechanical properties of 316L/304L stainless steels, Alloy 718 and Mod 9Cr-1Mo after irradiation in a spallation environment,” J. Nucl. Mater., 296 (July 2001) 119-128

[3] K. Farrell, T.S. Byun, and N. Hashimoto, Mapping Flow Localization Processes in Deformation of Irradiated Reactor Structure Alloys – Final Report, ORNL/TM-2003/63, (2003)

[4] J. Pawel, M. Grossbeck, A. Rowecliff, and K. Shiba, “Initial Tensile Test Results from J316 Stainless Steel Irradiated in the HFIR Spectrally Tailored Experiment,” US DOE Fusion Materials Semiannual Progress Report, Sept. 1994

[5] J. Pawel-Robertson, et al., “Tensile Test Results from J316 Stainless Steel Irradiated in the HFIR Spectrally Tailored Experiment,” US DOE Fusion Materials Semiannual Progress Report, Jan. 1996