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# Modeling tensile response and flow localization effects in 316SS after exposure to spallation and fission irradiation environments

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**Abstract**

The mechanical stability of structural materials under irradiation is a major concern for reactor component design and life cycle evaluation. The most important issue is the loss of ductility due to the development of radiation damage defect structures in the material. The acute loss of material tensile ductility is often characterized by a process where the material necks at very low uniform elongations in tensile loading, just following the yield point, a process commonly referred to as flow localization. The process where small tensile strains lead to plastic instability is examined through the analysis of tensile test data for 316SS irradiated either in a fission neutron spectrum or in a mixed proton and neutron spectrum characteristic of spallation sources. In both cases, it is found that uniform elongation levels are limited by a critical material strength. It is shown that there is a direct correlation between the material yield strength and the uniform elongation for the materials examined here. It is also shown that the large differences in He and H production between the two kinds of radiation environments have little or no effect on tensile properties. A further implication of the work is that the specifics of the post-yield flow and strain hardening processes are less important than the critical stress for determining the onset of plastic instability.
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## 1. Introduction

Type 316SS has been the most widely employed austenitic steel for irradiation applications. Despite limitations in thermal conductivity, swelling resistance, and resistance to stress corrosion cracking, this alloy has been used extensively in past nuclear applications and is slated for continued use in advanced nuclear systems including the spallation neutron source (SNS) and the ITER fusion device. The appeal of this material is that it is highly fabricable, weldable, and maintains reasonable ductility and fracture toughness in most applications. It has also been the basis for the development of low swelling and swelling resistant austenitic steel alloys. Low carbon versions, 316L SS, and low carbon with nitrogen additions versions, 316LN SS, have been developed to address stress corrosion cracking problems by

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reduction of carbon content, or replacement of carbon with nitrogen. Because of its widespread use as a structural alloy in a variety of nuclear applications, the mechanical stability of type 316SS as a function of radiation exposure has been a major point of concern. This alloy is susceptible to the development of very low tensile ductility due to irradiation in the temperature range of 150–400 °C [1,2]. This limitation is now well documented and shows that in a wide variety of 316SS and modified 316SS alloys, tensile ductility falls below 1% uniform elongation after doses as low as a few dpa in this temperature range. This process is often characterized as *flow localization* since the materials neck shortly after reaching their yield point in tensile loading. Because of the importance of this process to materials applications, ductility loss due to irradiation exposure has resulted in a large number of studies designed to understand the relationship between radiation-induced microstructural changes and their impact on materials elastic and plastic flow properties. These studies have concentrated on the dislocation multiplication, pinning and flow processes. These phenomena are typically used to model yield properties and flow processes just after yield.

In this study, the processes of radiation-induced loss of uniform tensile elongation and flow localization in 316SS are examined. Two major studies on flow localization effects of 316SS irradiated in fission spectra, one by Pawel-Robertson and co-workers [1,2] and a second recent study by Farrell, Byun and Hashimoto [3] were employed. In addition, a recent study on tensile properties of 316SS following exposure to a spallation-type neutron and proton irradiation spectrum were analyzed [4]. The distinction between these two types of irradiation spectra is important due to major differences in the amounts of He and H produced in addition to the displacement damage. For the studies of Pawel-Roberson et al., neutron energy spectrum tailored reactor irradiations were performed to produce He/dpa ratios of around 10 appmHe/dpa [1,2]. The other fission exposures produced a He/dpa ratio of on the order of 1 appmHe/dpa or greater depending primarily on the neutron energy spectrum, the Ni content and the levels of B impurities [3]. The spallation environment experiments, which in most cases included irradiation along the direct beam irradiation direction where proton irradiation accompanied the neutron irradiation, produced He/dpa ratios in the range of ~40 appmHe/dpa in SNS [5] to ~50 appmHe/dpa in LANSCE, depending on the relative numbers and energies of protons and neutrons [4,6]. In addition, substantial amounts of H are also produced in this spectrum and can be retained in the material following irradiation exposure [4]. It is also known that H storage can develop in typical fission reactor spectra, especially when large levels of He are also produced [7].

## 2. Analysis

Studies of loss of ductility in austenitic alloys have been on-going for over forty years. In austenitic stainless steels, this process is most apparent at intermediate temperatures, typically between 50 and 400 °C depending on the irradiation conditions. It is found that even small irradiation doses, on the order of a few dpa, are sufficient to reduce material uniform elongation to less than 1%. Fig. 1 shows selected engineering stress–engineering strain curves for 316L SS taken from the work of Maloy et al. [4]. The figure compares the tensile response for unirradiated and similar irradiation conditions at two tensile test temperatures, 50 °C and 164 °C. The tendency toward higher yield strengths and very low values of uniform elongation with irradiation dose is clear. For doses of around 8 dpa, the material shows uniform elongations of less than 1%. Perhaps a more striking feature of the curves is the strong temperature dependence of the tensile behavior. Even for the unirradiated conditions, a change in test temperature from 50 to 164 °C results in a major change in uniform elongation from a value of around 60% at 50 °C to a level of around 40% at 164 °C. For the 2.9 dpa irradiated case, the initial deformation is similar at 50 and 164 °C, but the material then fails at low uniform and total elongations at 164 °C. At 50 °C, the material continues to strain harden following the initial deformation behavior. By 8.8 dpa, the material is brittle and necks just following yield for both test temperatures, though even the necking deformation is different between the two cases.

For irradiation applications, it is normal to consider the changes in yield strength and uniform elongation as a function of dose. Fig. 2 shows the dose response of 316SS following the studies of Pawel-Robertson et al. [1,2], and Farrell, Byun and Hashimoto [3] and Malloy et al. [4]. Only selected data from these studies are

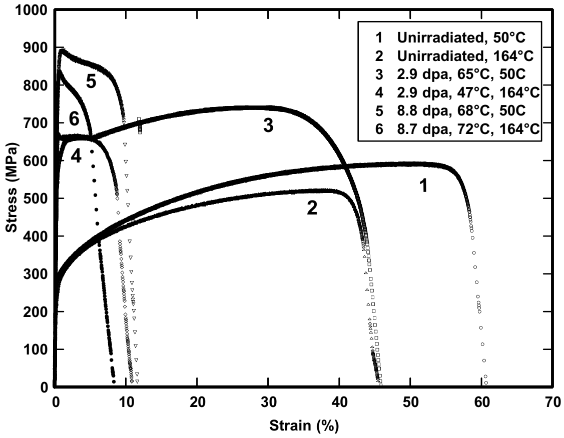

Fig. 1. Engineering stress–strain curves for 316L SS tested at 50 or 164 °C [4].

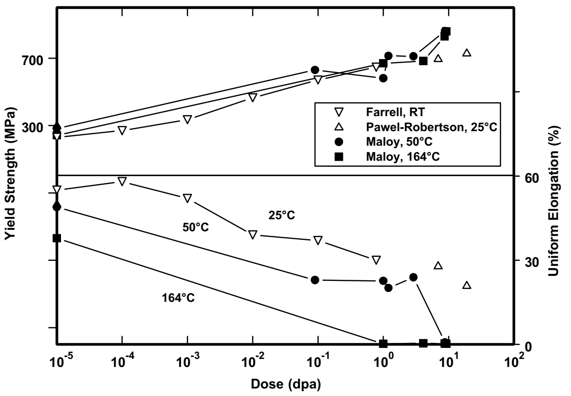

Fig. 2. The relationship between irradiation exposure dose and yield strength and uniform elongation for type 316SS [1–4].

plotted here for clarity in the figure. The data from Farrell et al. [3] are plotted as the average values from multiple tests at each dose and tested at room temperature. Averaged data for 25 °C tensile tests from the studies of Pawel-Robertson et al. [1,2] are also shown. All available data points from the Maloy et al. study [4] are shown. The figure indicates that within moderate limits, the radiation-induced increases in yield strengths are similar in all cases (this will be examined in detail later), whereas the uniform elongation response has a strong temperature dependence.

In addition to the strong temperature dependence, there seems to be a strong correlation between the increase in yield strength and decrease in uniform elongation. In Fig. 3, uniform elongation is shown as a function of yield strength for all of the data in the Pawel-Robertson studies [1,2] and for the Farrell, Byun and Hashimoto study [3]. The Pawel-Robertson data at 25 °C are shown with a least squares linear fit, as are the Farrell et al. data. While there are slight differences in the data sets, the fits are remarkably similar, with nearly the same slope. The Pawel-Robertson data at 400 °C were also fit with a linear least squares fit. This fit seems to be a reasonable representation the all of the data from those studies at temperatures between 200 and 400 °C. The curve also seems to be a reasonable fit to the data from the Farrell et al. study for specimens tested ate 288 °C. The strong difference in temperature dependence of the two sets of curves, the ones near room temperature and the ones between 200 and 400 °C, is apparent.

Fig. 3 also indicates that the tensile test temperatures plays a more important role in the tensile response than does the irradiation temperature. Three data points that were tensile tested at a temperature different than the irradiated temperature are indicated. These points are best associated with the tensile properties trends according to test temperature rather than irradiation temperature.

Fig. 4 shows the data from the Maloy et al. studies [4] with the data trends from Fig. 3. Again there is a strong temperature dependence in the tensile response between tests performed at 50 °C and at 164 °C. One data point at 25 °C is also shown. The data trends show a different slope than those in Fig. 3. This seems to be a result of the differences in yield strengths of the starting materials. In fact, the point of near zero uniform elongation for the 164 °C tests intersects the yield strength axis at nearly the same point as that from the Pawel-Robertson studies at about 700 MPa. The tensile tests at 50 °C indicates that an intersection of the line with the yield strength axis falls at about 900 MPa.

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

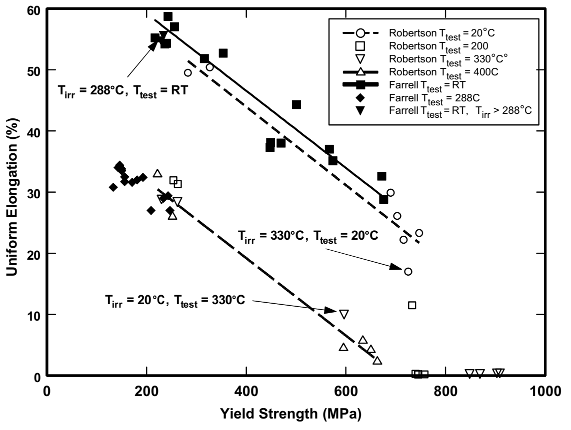

Fig. 3. The relationship between uniform elongation and yield strength for 316SS [1–3].

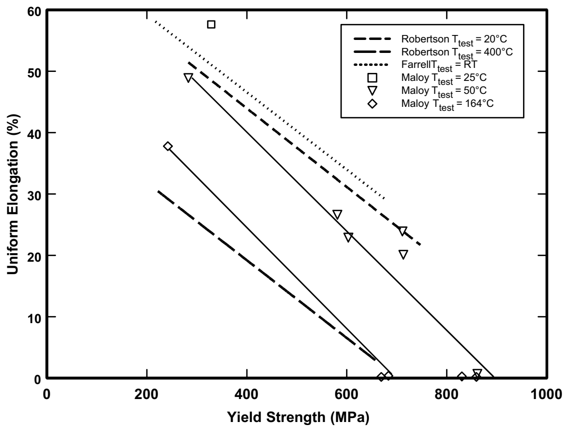

Fig. 4. Uniform elongation versus yield strength for 316L SS irradiated in a spallation particle spectrum and tested at 50 or 164 °C [4]. The data for Maloy et al. [4] are compared to the data trends in Fig. 3.

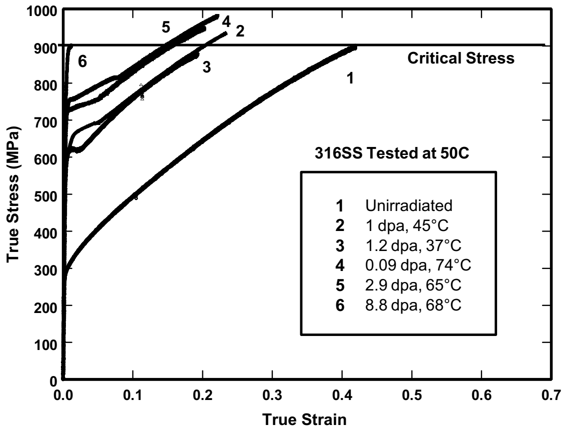

Fig. 5. True stress–strain plot for 316L SS irradiated tested at 50 °C. The irradiation doses and temperatures are indicated in the legend [4].

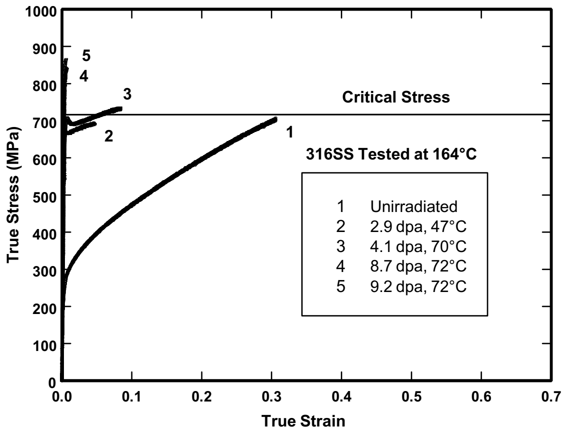

Fig. 6. True stress–strain plot for 316L SS irradiated tested at 164 °C. The irradiation doses and temperatures are indicated in the legend [4].

upon yielding. This point is consistent with the true stress level at necking for all tensile curves regardless of radiation damage level. The true stress–true strain curves for the Maloy et al. tensile tests are shown in Fig. 5 for 50 °C and in Fig. 6 for 164 °C. Fig. 5 shows that the true stress to necking is approximately 900 MPa at 50 °C and about 700 MPa at 164 °C, which are the same as the intersection points of the trend curves with the yield strength axis for those two temperatures in Figs. 3 and 4.

## 3. Discussion

This study shows that there is the strong correlation between material yield strength and uniform elongation, which is independent of irradiation condition. The relationship, however, seems to have a very strong temperature dependence for 316SS, particularly between the temperatures of 20 and 150 °C. This relationship has a number of consequences, but perhaps the important consequence for assessing flow localization in irradiated 316SS is that the mode of deformation, which affects the yield point and the post-yield strain hardening, has little influence on the onset of necking. Once the critical stress is reached, regardless of the operating flow mechanisms, the material will suffer plastic instability. Irradiation-induced hardening can increase the yield strength so that only a small amount of plastic flow occurs before necking, but the necking process itself seems to be controlled by other mechanisms.

A second important finding is that the true stress to failure is a material property and not a function of radiation-induced defect microstructure, dislocation multiplication mechanisms or strain hardening behavior. For 316SS, the reasons for the strong temperature-dependent critical stress are not known at present. Fig. 7 shows the average values of yield strength and critical stress as a function of tensile test temperature. These data show that while the yield strength shows a very slight drop in value over the temperature range, the critical stress for plastic instability drops drastically between 20 and 150 °C. Other materials properties, such as stacking fault energy or elastic modulus, also show a modest change over the temperature range in question. Farrell, Byun and Hashimoto have also recently report a universal plastic instability stress (PIS) for fcc materials [8].

From the preceding discussion, it is apparent that the flow properties and the point of plastic instability, i.e. the critical stress, are not affected by irradiation exposure. This means that the same microstructural properties control plastic instability regardless of radiation

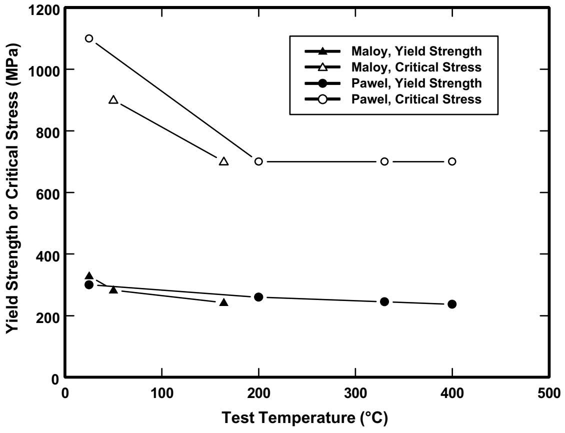

Fig. 7. The dependence of the unirradiated yield strength and the critical stress for 316SS [1,2,4].

damage microstructure. This is associated with the nucleation, growth and coalescence of plasticity-induced voids. These processes have received considerable attention in the literature (see, for example, Refs. [9–11]) where plasticity-induced void formation processes have been modeled following Gurson [12,13]. The least well characterized of these processes is the plasticity-induced void nucleation process. In much of the work to characterize the plasticity-induced void nucleation process, a highly stress or strain dependent functional relationship is assumed, see Refs. [9,10]. The functional form, however, is not related directly to easily accessible materials parameters. The nucleation process should be dependent on the type and distribution of nucleation sites and surface energies required to form new internal surfaces. Nucleation processes which depend on a distribution of particles or inclusions have been reviewed by Goods and Brown [14]. Their review suggests that particle-matrix interfacial strengths are the controlling factor. The current findings indicate that the distribution of plastic void nucleation sites is affected by radiation exposure for the conditions examined in this study.

An interesting point of comparison is the influence of cold work on the critical stress. The studies of Pawel-Robertson et al. [1,2] included specimens with 20% cold work. The uniform elongation versus yield strength behavior is shown in Fig. 8 for these conditions and compared to the values for solution annealed 316SS. It can be seen that cold working lowers the critical stress for plastic instability to a value of about 850 MPa compared to an extrapolated value of around 1100 MPa in the solution annealed material at 25 °C. The uniform elongation values for cold worked 316SS tensile tested at 200, 330 and 400 °C are all low, but seem to approach zero by 700 MPa or perhaps lower stress levels. The drastic reduction in critical stress, at least at lower temperatures, would seem to indicate that the initial strength advantages that would derive from cold working have a detrimental effect on flow localization and fracture properties.

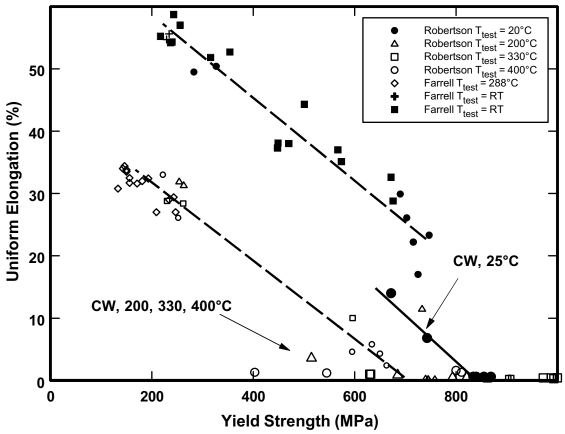

Fig. 8. The influence of cold work on the uniform elongation versus yield strength behavior of 316SS [1,2]. Cold worked materials are shown with the larger size symbols compared to the annealed 316SS data from Pawel-Robertson [1,2] and the data from Farrell et al. [3].

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, $\varepsilon_u$, can be predicted by equations of the form

$$\begin{aligned} \varepsilon_u &= \varepsilon_u^0 - m \cdot \sigma_{ys} && \text{for } \sigma < \sigma_{crit}, \\ \varepsilon_u &\sim 0 && \text{for } \sigma \geqslant \sigma_{crit}, \end{aligned}$$

where $\varepsilon_u^0$ 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. A comparison of the data for Maloy et al. [4] and the group of studies by Pawel-Roberson, Farrell et al. [1–3], indicate that, while the initial material yield strengths are different, the critical stress levels are very nearly the same. Thus the slope values, $m$, in the equations would vary drastically depending on the starting material properties. This can be seen by comparing the slopes and intercepts shown in Fig. 4.

A final point of interest is the influence of He and H to dpa ratios on the tensile response. The current analysis would indicate that He and H have little influence on flow localization of plastic instability response in the materials studied here. The data represent a wide range of He to dpa and H to dpa ratios, He/dpa range from as low as 1 appmHe/dpa to a value between of more than 50 appmHe/dpa, but little differences are found in the tensile properties related to necking and plastic instability. This conclusion is consistent with other studies of these influences, and confirms that He and H have relatively little impact on flow instability for the conditions discussed above.

## 4. Conclusions

Analysis of the tensile response of selected series of unirradiated and irradiated type 316SS tests was carried out to establish the tendency for plastic instability and flow localization. A strong, linear correlation between the uniform elongation and the yield strength was found for the materials conditions studied here. The point of intersection of the linear uniform elongation–yield stress trend line with the yield stress axis is defined by the critical stress for plastic instability. This critical stress is the true stress value associated with the material ultimate tensile strength. The critical stress seems to be a material property and exhibits a very strong temperature dependence between 20 and 150 °C in 316SS. The critical stress is not dependent on the characteristics of the irradiation and is not influenced by the He to dpa ratio for the conditions examined here. Cold working does seem to influence the critical stress value by reducing it substantially at room temperature. Further work is required to clarify the plasticity-induced void nucleation processes that control the critical stress value.

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