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Modeling tensile response and flow localization effects in selected copper alloys

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Abstract

Radiation-induced defect structures are known to elevate material yield strength and reduce material ductility. Together, these changes substantially reduce uniform elongation compared to the unirradiated material condition so that the small strains induce plastic instability. This process, commonly known as flow localization, is examined here for selected copper alloys and compared to similar response in 316SS. It is found that uniform elongation levels are limited by a critical material strength which is independent of the irradiation damage state. This result establishes that the details of the post-yield flow and strain hardening processes are less important than the critical stress for controlling plastic instability. In the case of OFHC Cu, post-irradiation heat treatment restores some initial ductility, but also reduces the critical stress for incipient flow localization.

1. Introduction

It has long been known that exposure of most, perhaps all, structural materials to irradiation induces an increase in material yield strength and an accompanying reduction in ductility. This effect is of particular concern when the loss of ductility translates into small uniform flow during deformation leading to flow localization and necking. Loss of material ductility is also often reflected in reduced fracture toughness. These effects reduce the ability of materials to distribute plastic flow uniformly during deformation, and thus limit material useful life in radiation environments. Because of its importance, 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 tensile and plastic flow properties.

In this study, the tendency for flow localization is examined in copper alloy systems, which are of considerable interest for fusion systems applications, and compared to similar behavior found for 316SS. The process is examined by analysis of tensile properties with and without exposure to irradiation. This work concentrates on limited ductility and flow localization in irradiated copper alloys by Edwards and co-workers [1,2]. For irradiated 316SS, two major studies on flow localization effects in 316SS, one by Pawel-Robertson and co-workers [3,4] and a second recent study by Farrell et al. [5] were examined.

2. Analysis

Studies of flow localization in fcc and austenitic alloys have been on-going for over 40 years. This process is most apparent at intermediate temperatures, typically between 50 and 400 °C depending on the material, where even small irradiation doses, on the order of a few dpa, are sufficient to reduce material uniform elongation to less than 1%. In the copper alloy system, the tendency

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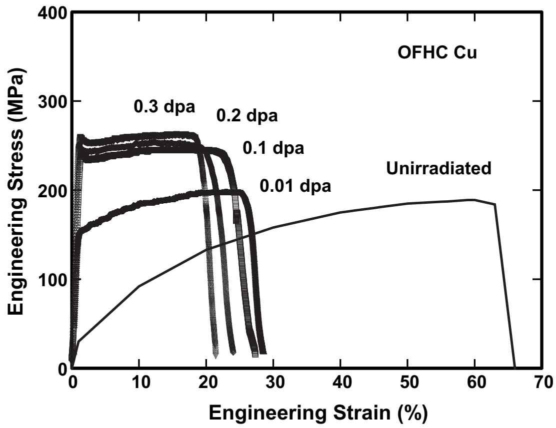

Fig. 1. Engineering stress–strain curves for unirradiated and irradiated OFHC Cu tested at 100 °C [4].

for flow localization occurs at very low doses, less than 1 dpa, for alloys irradiated at around 50 °C. Fig. 1 shows typical stress–strain curves for OFHC copper irradiated to various low doses at 100 °C and tensile tested at 100 °C [1]. The trend toward localized flow in this material is evident in the elevation of the yield strength and the reduction in the uniform elongation with irradiation dose. The increase in yield strength, in itself, is not seen to be problematic, rather the much lower strain levels at which plastic instability or necking occurs present the major concern. The tendency for fully localized flow is more evident in OFHC Cu irradiated and tested at 50 °C [2]. The relationship between the dose and changes in yield strength and uniform elongation are shown in Fig. 2 for several copper alloys [1,2]. The results show the reasonably systematic elevation of yield strength and systematic decline of uniform elongation with dose. In

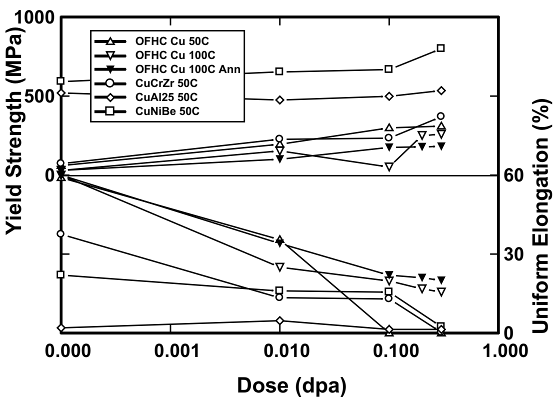

Fig. 2. The relationship between irradiation exposure dose and yield strength and uniform elongation for 316SS [1–4]. Note that some of the data are plotted as the average of several tests (see text).

one case, that of CuAl25, there is a modest radiation-induced softening of the highly dislocated microstructure due to initial irradiation exposure. A comparison of the results at 50 and 100 °C for OFHC Cu shows that the tendency for flow localization occurs at a lower dose for the 50 °C irradiation and test temperatures than for the 100 °C irradiation and test temperatures. A uniform elongation of less than 1% is found at the lower test temperatures for doses as low as 0.1 dpa, whereas at doses up to 0.3 dpa, the 100 °C irradiated material still has reasonable ductility. For the other copper alloy cases, it can be seen that the uniform elongations all fall below 1% by doses of 0.3 dpa at 50 °C.

The general trend for these alloys to concurrently harden and embrittle during radiation exposure, as indicated in Fig. 2, suggests some correlation between these two properties. Fig. 3 shows the relationship between yield strength and uniform elongation for OFHC copper and selected copper alloys and includes similar data for 316SS from more detailed studies of that alloy system [3–7]. It is apparent that, within the limits of the scatter in tensile testing results, there are clear linear relationships between yield strength and uniform elongation for the copper alloys. It is also apparent that similar relationships exist for 316SS with a major difference in the trend line for test temperatures of around room temperature and at elevated temperatures between 200 and 400 °C.

The linear correlations for copper and its alloys differ widely in magnitude and slope. This would be expected due to the differences in operating hardening mechanisms among the alloys. In the case of CuAl25, there are only minor differences between unirradiated and irradiated ductilities. The low ductility of this alloy has been well established and is due largely to the particle strengthening and small grain size effects. In addition, the strength and ductility are dependent on orientation due to the strong directionality in the material microstructure due to the material consolidation and fabrication process. For the other copper alloys, the CuCrZr, which has an initial strength comparable to OFHC Cu but somewhat lower ductility, nevertheless reaches a near zero uniform elongation at about the same stress level, about 300 MPa, similar to OFHC Cu. The CuNiBe alloy has a higher strength and lower initial ductility than the other copper-based materials, but does show a shallower slope with radiation-induced hardening.

The data for OFHC Cu include specimens irradiated and tested at 50 °C (filled downward triangles in Fig. 3) and specimens irradiated and tested at 100 °C (filled upward triangles in Fig. 3). Despite the difference in irradiation and test temperature, these data show a very similar correlation between yield strength and uniform elongation. It is important to note that these two materials showed different hardening dependences with dose (see Fig. 2), but still fall on the same line for yield

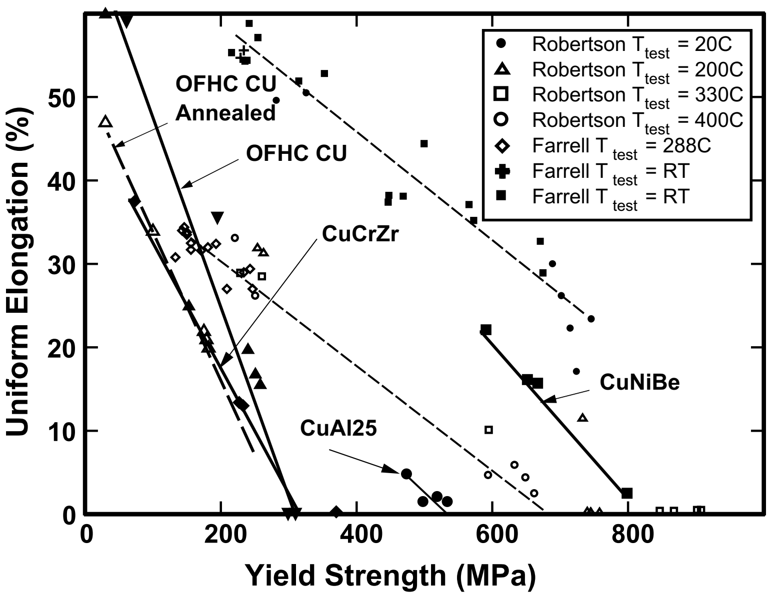

Fig. 3. The relationship between uniform elongation and yield strength for selected copper alloys shown with larger symbols [1,2] compared to trends for copper and copper alloys shown with smaller symbols and keyed to the legend [4–7].

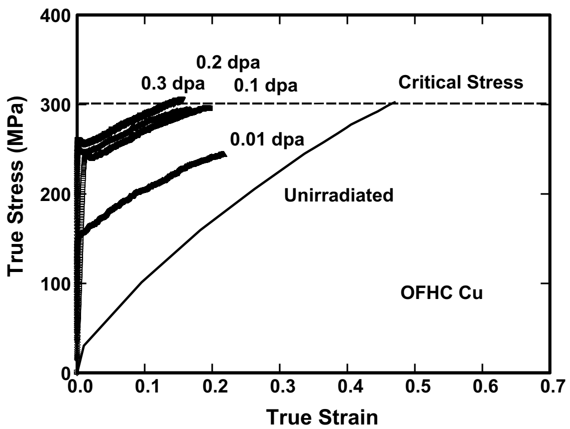

Fig. 4. True stress–strain plot for OFHC Cu irradiated at 100 °C and tensile tested at 100 °C [1]. These are the same data shown in Fig. 1.

strength to uniform elongation correlations (see Fig. 3). This indicates that the relationships shown in Fig. 3 are reasonably independent of the radiation hardening kinetics.

In each case, there appears to be a critical stress limit at which plastic instability occurs. This is the points at which the trend lines intersect the yield strength axis. This is, in fact, the point at which the material yield strength equals the stress for plastic instability. For cases where the material yield strength has reached or surpassed this critical level, the material will neck as soon as tensile yield is reached. This critical stress limit is found to be independent of yield strength and strain hardening characteristics. This stress is equivalent to the true stress corresponding to the material ultimate strength. An example of this can be seen in Fig. 4 for OFHC Cu irradiated and tested at 100 °C. Fig. 4 shows the true stress–true strain behavior for the same set of conditions shown as engineering stress–engineering strain in Fig. 1. The true stress at necking is constant regardless of the irradiation dose, the yield point, or the strain hardening behavior of the material. It is also important to note that this stress level is exactly the same stress as the intersection of the OFHC Cu curve with the yield strength axis in Fig. 3.

3. Discussion

The major outcome of this analysis is that a critical stress limit for plastic instability exists which is independent of yield strength and post-yield strain hardening behavior. The limit appears to be an inherent material or alloy property. This also applies to 316SS which is examined in more detail elsewhere [6]. This result suggests that the dynamics of dislocation pinning, multiplication and flow are secondary to the material property that controls plastic instability. This is confirmed by other recent work by Byun et al. [7].

Edwards and Singh performed an in-depth study of the deformation microstructure of the OFHC Cu alloys [8]. In that work, there are clearly different dislocation flow mechanisms operating depending on irradiated state. Despite major differences in dislocation dynamics in the group of OFHC Cu specimens, each material condition failed consistently at the same critical stress level.

As part of the OFHC Cu study at 100 °C, specimens with various levels of irradiation exposure were annealed at 300 °C for 100 h [1,8]. The specimen irradiation conditions matched those in Figs. 1 and 4. The annealing process eliminated the sharp yield point and recovered some of the material ductility. The true stress–true strain curves for these conditions are shown in Fig. 5. While the annealing process resulted in some recovery of tensile properties, it also lowered the critical stress for plastic instability. The value following annealing is roughly 30 MPa lower than the value for the as-irradiated condition. The uniform elongations and yield strengths for these specimens are shown in Fig. 3 (unfilled upward triangles). The yield strength to uniform elongation data again show a linear relationship which would extrapolate to the yield strength axis at about 270 MPa, consistent with the critical stress determined from the true stress limit in Fig. 5.

This behavior suggests a simple relationship for predicting uniform elongation or plastic instability based on the linear correlation with materials yield strength. The level of uniform elongation can be predicted by equations of the form

$$\varepsilon_u = \varepsilon_u^0 - m \cdot \sigma_{ys} \quad \text{for} \quad \sigma < \sigma_{\text{crit}},$$

$$\varepsilon_u \sim 0 \quad \text{for} \quad \sigma \geqslant \sigma_{\text{crit}},$$

where ε_u^0 is the intercept on the uniform elongation axis and m is the slope of the trend line. This relationship is somewhat limited by the realization that, while the critical stress seems to be fixed, the initial material yield strength and uniform elongation values could vary due to differences in starting microstructure. Thus the values of ε_u^0 and m will be set by the initial material condition. Note that this relationship does not include any explicit dose dependence. Rather, the dose dependence would be included through its influence on the value of yield stress.

The precise materials deformation processes that control the critical stress level are not yet clear. The point of plastic instability in tensile deformation is most often associated with the nucleation, growth and coalescence of plasticity-induced voids. This multistage process has received considerable attention in the literature (see for example Refs. [9–11]). Of these steps, the least well characterized is the plasticity-induced void nucleation process. Attempts to characterize the nucleation process have focused on the role of particles and particle-matrix interfacial strength [12]. This approach has limited application to OFHC Cu where particulate strengthening does not play a role. Other work on pure metal systems [13] showed similar response for irradiated pure Ni, with a very similar critical stress level of around 300 MPa. Results in the same study for pure Au are somewhat less consistent with critical stress levels. One study of a particulate strengthened copper alloy system, Cu–SiO_2, showed low strains to failure, consistent with the CuAl25 behavior here [14]. In the current systems, there does not seem to be an indication of a direct radiation-induced effect on the critical stress level. However, if interfacial stresses, or perhaps, grain boundary strengths play a role in the necking process, radiation-induced segregation effects could directly influence the failure process. These observations indicate that precise processes that lead to plastic instability require further study.

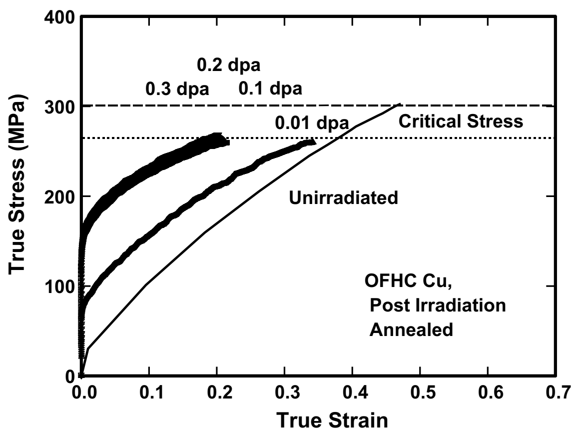

Fig. 5. True stress–strain plot for OFHC Cu irradiated at 100 °C and post-irradiation annealed for 100 h at 300 °C. Tensile tests were performed at 100 °C [1].

4. Conclusions

Analysis of tensile response of a variety of irradiated copper alloys was carried out to establish the characteristics that control the plastic stability limit. This limit, most often characterized by uniform tensile elongation and initiation of necking, seems to be controlled by a critical stress which is independent of the operating yield and post-yield strain hardening behavior. A strong, linear correlation between the uniform elongation and the yield strength does exist for the copper alloys examined 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 behavior in these copper alloys is similar to that found in 316SS.

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