POST-IRRADIATION ANNEALING RESPONSE OF PURE COPPER IRRADIATED AT 100°C - D.J. Edwards (Pacific Northwest National Laboratory)*, B.N. Singh, P. Toft and M. Eldrup (Risø National Laboratory)

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EXTENDED ABSTRACT

Pure copper and its alloys have long been evaluated for use in fusion reactor designs because of the need for a heat sink material with sufficient thermal conductivity to handle the high heat loads in the plasma facing components. Recent investigations have demonstrated that copper and copper alloys suffer from the irradiation-induced loss of ductility and plastic instability when irradiated at temperatures below the recovery stage V [1-5]. This behaviour has also been observed in fcc, bcc and hcp metals and alloys (see Ref. 6 for a recent review on this topic). The source of the radiation hardening is derived from the radiation-produced damage processes that yield a high density of small defect clusters that are both sessile and glissile depending on their size and nature (vacancy or interstitial). The presence of these defect clusters produced during irradiation can cause substantial changes in the mechanical and physical behaviour of the material, including the loss of uniform ductility and work hardening, large increases in yield strength, formation of a yield drop, and overall loss of conductivity. The changes in the deformation behavior of the material are particularly worrisome given that the formation of the yield drop often signifies the onset of plastic instability (dislocation channelling or microtwinning) during deformation. Several issues remain unclear, in particular the actual mechanism responsible for the yield drop, why a given material will experience work softening or work hardening depending on the dose, and how these changes in deformation mode will affect the cracking susceptibility.

One issue that bears further study is the possibility of being able to anneal the radiation damage out of the irradiated material, for example, during the periodic bakeout of the vessel chamber needed to improve the vacuum. This is a complicated issue since the microstructure evolves over time, and the annealing may in fact produce different results depending on when the anneal is done, that is, at doses of 10^{-2} dpa versus 0.5 dpa. Further complicating the issue is how multiple cycles of annealing and irradiation may affect the microstructural evolution over the lifetime of the component. As a first step toward investigating the effect of annealing on irradiated copper, tensile samples of pure copper (annealed at 550°C for 2h in vacuum, 10^{-6} torr) were irradiated in the DR-3 reactor at Risø National Laboratory at 100°C to different dose levels in the range 0.01 to 0.3 dpa (NRT). All specimens were irradiated with a displacement damage rate of ~5 x 10^{-8} dpa (NRT)/s. A subset of the irradiated specimens were given a post-irradiation annealing treatment under vacuum (<10^{-5} torr). Microstructural examinations have been completed for both the as-irradiated and the post-irradiation annealed samples, and results of the preliminary tensile tests (strain rate of 1.2 x 10^{-3} s^{-1}, 100°C in vacuum, <10^{-4} torr) are available also. Electrical resistivity measurements have already been reported separately [7].

The microstructure contains a high density of small stacking fault tetrahedra (SFT's) and line dislocations that were present before irradiation. The size distributions of the SFT's in the as-irradiated samples are shown in Figure 1 as a function of dose. A slight broadening of the

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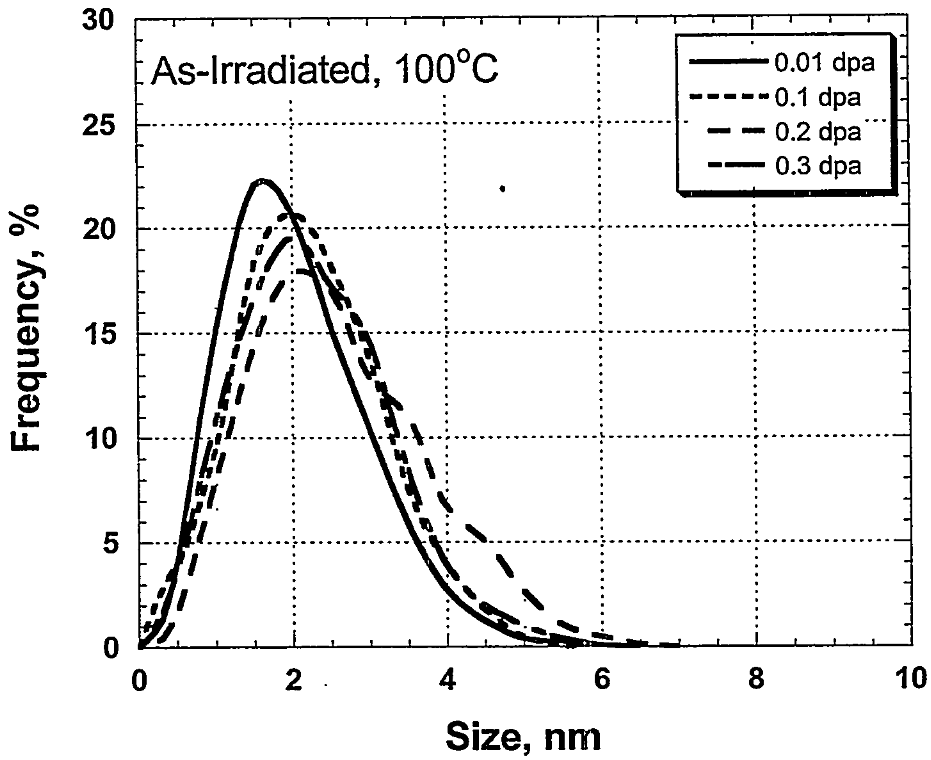

Figure 1. The size distributions for the as-irradiated pure copper are shown, and reveal that irradiation from 10^{-2} to 0.3 dpa produces only slight differences in cluster sizes. The average size of ~2.5 nm is similar for all four conditions.

overall distribution occurs as the dose increases, with the average size staying at bout ~2.5 nm. The effect of post-irradiation annealing on the size distribution of the SFT's is presented in Figure 2, showing that annealing causes a noticeable shift toward larger sizes as well as an overall broadening of the size distribution. However, for the samples irradiated at 0.3 dpa and then annealed, the average size is actually smaller than that of the samples irradiated to 0.1 and 0.3 and then annealed. The dose dependence of the cluster densities shown in Figure 3 for the as-irradiated and post-irradiation annealed samples also demonstrate the effect that annealing has on the microstructure. The cluster densities after annealing are lower than that measured in the as-irradiated samples, and this is particularly true for the 10^{-2} dpa samples where the difference is almost a factor of 5. The annealed 0.3 dpa sample, however, is within a factor of 2, basically within the experimental scatter. Note that the cluster density for the annealed 0.3 dpa sample is almost the same as that of the as-irradiated 10^{-2} dpa sample, but with a larger average size.

The tensile properties are given in Table 1, and show that the as-irradiated samples exhibit a large increase in yield strength even at 10^{-2} dpa. The uniform and total elongation decrease

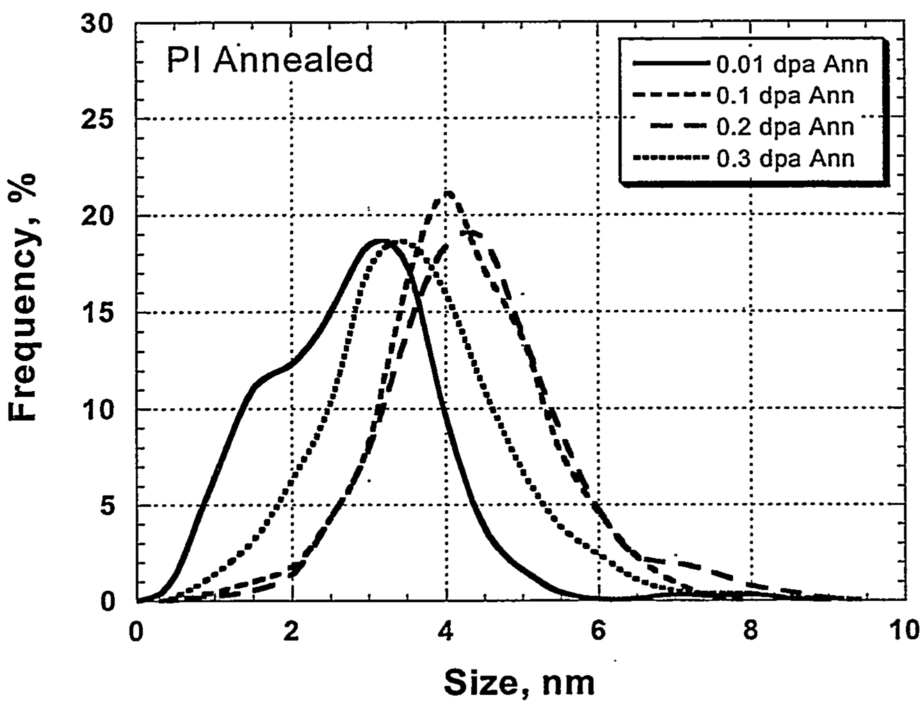

Figure 2. Post-irradiation annealing increases the overall size of the clusters and broadens the size distributions compared to the same dose in the as-irradiated condition. The annealed 0.3 dpa condition has a smaller average size than 0.1 dpa and 0.2 conditions, but the reasons for this are not presently known.

substantially in the as-irradiated samples, and in fact disappear entirely after irradiation to 0.1 dpa and above. A sharp yield point begins to appear even at 10^{-2} dpa, and evolves into an upper and lower yield point at the higher doses. Work hardening after irradiation is negligible after 0.1 dpa and above, and essentially the upper yield strength and ultimate strength are the same due to the poor work hardening ability. Annealing has a profound effect on the mechanical properties, and restores the work hardening ability and uniform elongation of the material at all doses. However, the yield strength remains considerably higher and the ductility lower than that measured for the unirradiated specimens, which agrees with the fact that the microstructure still retains a high cluster density. It is important to note that no yield point is present in the annealed 0.3 dpa sample even though the cluster density is the same as the as-irradiated 10^{-2} dpa sample and the average size is larger. Microstructural examination of the deformed samples from the as-irradiated samples show that dislocation channelling occurs in all conditions, but the degree of dislocation channelling is higher the greater the yield strength and more prominent the yield drop. While dislocation channels are still observed in the annealed and deformed samples, significant dislocation motion in those

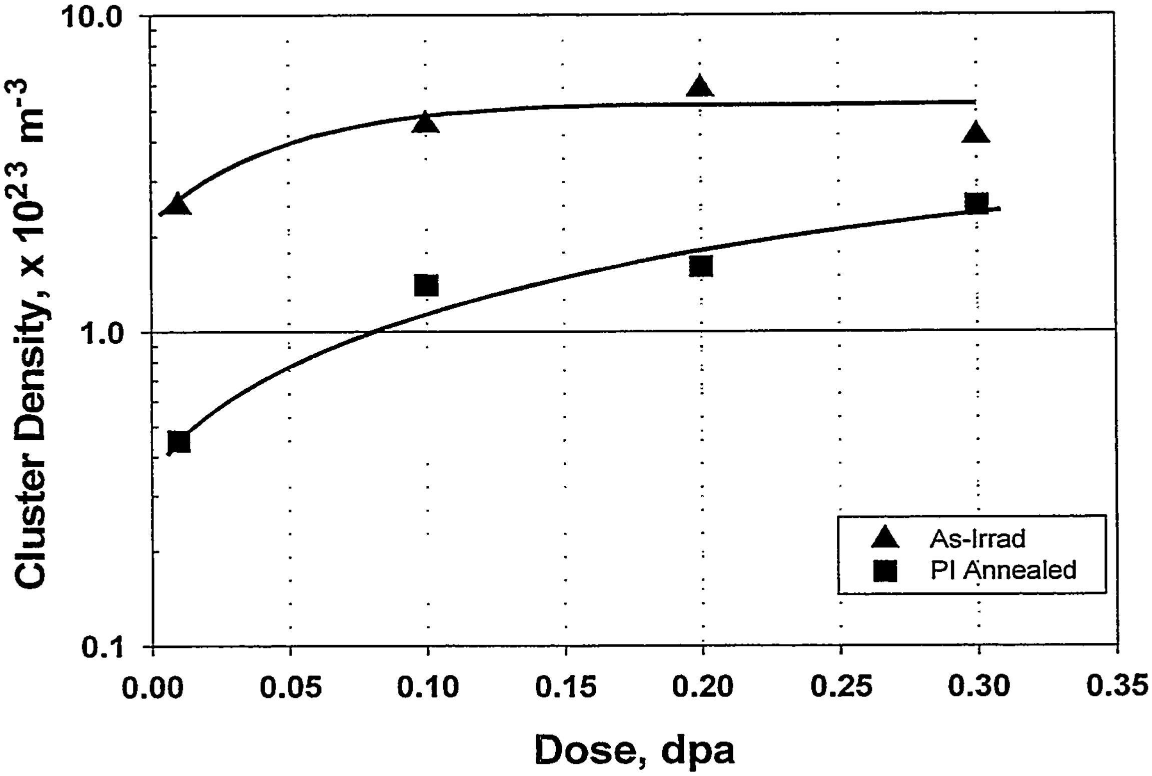

Figure 3. The density of the clusters saturates at about 0.1 dpa in the as-irradiated condition in agreement with results presented in the literature at similar irradiation temperatures. The density in the post-irradiation annealed condition is significantly lower at 10^{-2} dpa compared to its as-irradiated counterpart, but the density begins to approach that of the as-irradiated samples as the dose increases. The high density of clusters and smaller size distribution at 0.3 dpa suggests that the annealing kinetics can change as the microstructure evolves.

Table 1. Tensile properties of OFHC-copper and different copper alloys in the unirradiated, as-irradiated and post-radiation heat treated conditions

Dose [dpa]	Post irr. heat treat. [°C]	σ_y^u [MPa]	$\sigma_{0.2}$ [MPa]	σ_{max} [MPa]	ε_u^p [%]	ε_t [%]
Unirr	-	-	30	190	56	63
0.01	-	-	155	195	24	26
0.1	-	245	-	245	-	23
0.2	-	250	-	250	-	20
0.3	-	265	-	265	-	22
0.01	300°C for 50 h	-	68	170	39	43
0.1	300°C for 50 h	-	135	208	25	28
0.2	300°C for 50 h	-	145	215	24	26
0.3	300°C for 50 h	-	150	220	23	26

areas in-between the few channels is observed that explains why the material exhibits a more normal work hardening behavior.

The formation of the upper and lower yield point is thought to be due to the dislocations being decorated in a manner analogous to that of the solute atoms that form the Cottrell atmosphere in pure Fe [8]. Singh, Foreman, and Trinkaus [6] proposed a new mechanism called Cascade-Induced Source Hardening (CISH) where the grown-in dislocations are decorated by small dislocation loops or clusters formed during irradiation. The possibility also exists that impurities are segregated to the dislocations, a factor which may be more prominent in the case of alloys. The CISH mechanism seems to be supported by the annealing results. Although the density of clusters remains high and the size of the clusters is larger after annealing, normal work hardening occurs during the tensile test without any evidence of a yield drop. This implies that annealing effectively removes or decreases the degree of dislocation decoration and unlocks the grown-in dislocation sources. The clusters in the matrix still contribute to the overall strength of the material since dislocations moving through the matrix must interact with the sessile loops, but these interactions are thought to be rather weak in comparison to the dislocation decoration. Further analysis of the deformed microstructures and overall behavior is needed, and the results will be evaluated in light of the CISH model and the traditional "dispersed barrier" model to explore the radiation-induced increase in yield strength.

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