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MS-14-P-3196 TEM investigation of He bubbles in 9%Cr ferritic steel after neutron irradiation

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To provide quantitative microstructural information on helium bubble development under the influence of irradiation, 3 heats of EUROFER 97 composition with the addition of natural boron as well as pure 10B isotope were fabricated. He concentrations after irradiation were ~81, ~415, and ~5800 appm for these three specimens (alloy 1, alloy 2 and alloy 3), respectively. Neutron irradiation with a dose of up to 16 dpa was performed in the temperature range from 250°C to 450°C. This allowed for a detailed study of the influences of radiation parameters on the size, morphology, spatial distribution, and density of He bubbles. These investigations are necessary to correlate radiation-induced changes of the microstructure to the mechanical properties.

The cavities were not detected in alloys 1 and 2 irradiated at 250°C. Irradiation at this temperature leads to the formation of point defects and dislocation loops of 5-10 nm in size (Figs. 1a, 2a). However, their spatial density that exceeds bubble density by one order of magnitude, increase further strength and hardness which are dominated below 350°C by irradiation induced interstitial type loops. Irradiation at 400°C produces clear differences in the microstructures of alloy 3 due to the 5800 appm He content. The randomly distributed cavities and bubbles were detected in the specimen irradiated at 350°C (Fig. 1b,2b). The cavities exhibit a mainly faceted shape, which indicates the formation of empty voids rather than filled bubbles. In the alloys 1 and 2 irradiated at 450°C, no formation of faceted voids was detected, the He-filled bubbles were mainly located in dislocations, precipitates, or grain boundaries. The bubbles are smaller than 10 nm and show a sharp size distribution with a maximum at 5 nm. In some cases, bubbles are located on dislocations forming a 2-dimensional net (Fig. 2c). The density of bubbles in the specimens irradiated at this temperature depends on the He concentration: $2.4*10^{21}$ m^{-3} for alloy 1 with 82 appm He and $8.1*10^{21}$ m^{-3} for alloy 2 with 415 appm He. The presented TEM investigations of irradiated material clearly show the strong influence of transmutation-produced He on the formation of He bubbles or cavities. It can be supposed that faceted cavities >10 nm, similar to the imaged individual bubble in Fig. 1b-2b, are empty voids.

The HRTEM investigations of an individual cavity are shown in Fig. 3. The image (a) and the Fast Fourier Transformation (FFT) pattern (b) exhibit the orientation of the cavity’s facets. The cavities often show a hexagonal shape, the facets are oriented in <110> directions, if the matrix is oriented close to the [111] zone axis.

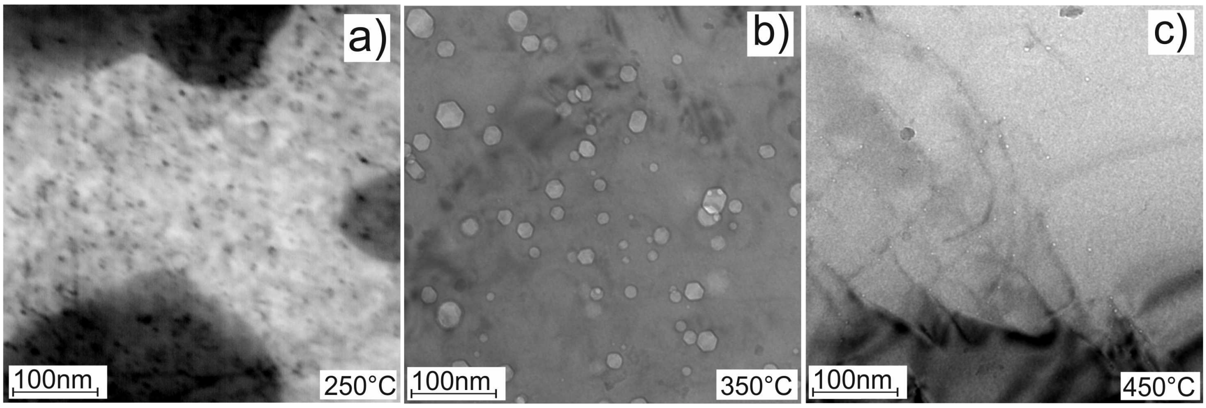

Fig. 1: TEM images of alloy 1 irradiated at 250°C 350°C, and 450°C are shown in parts a, b, and c, respectively.

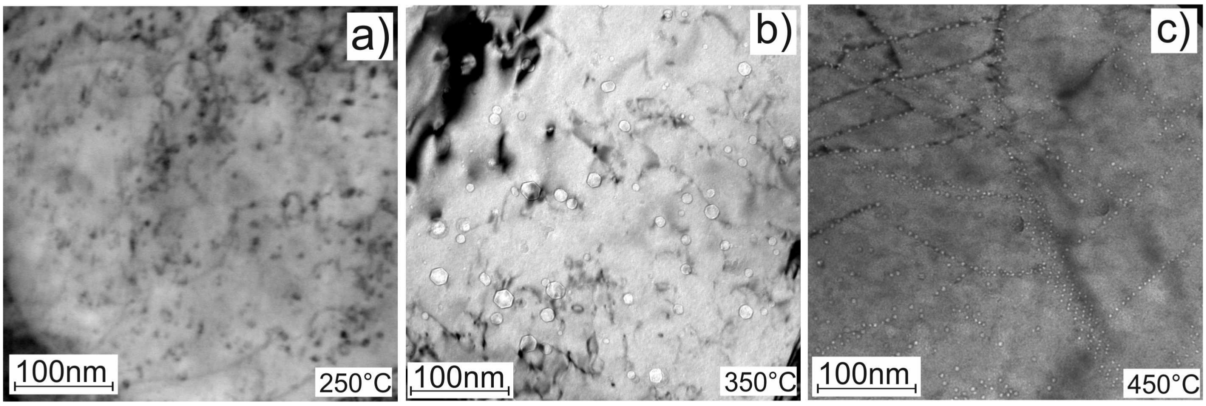

Fig. 2: TEM images of alloy 2 irradiated at 250°C 350°C, and 450°C are shown in parts a, b, and c, respectively.

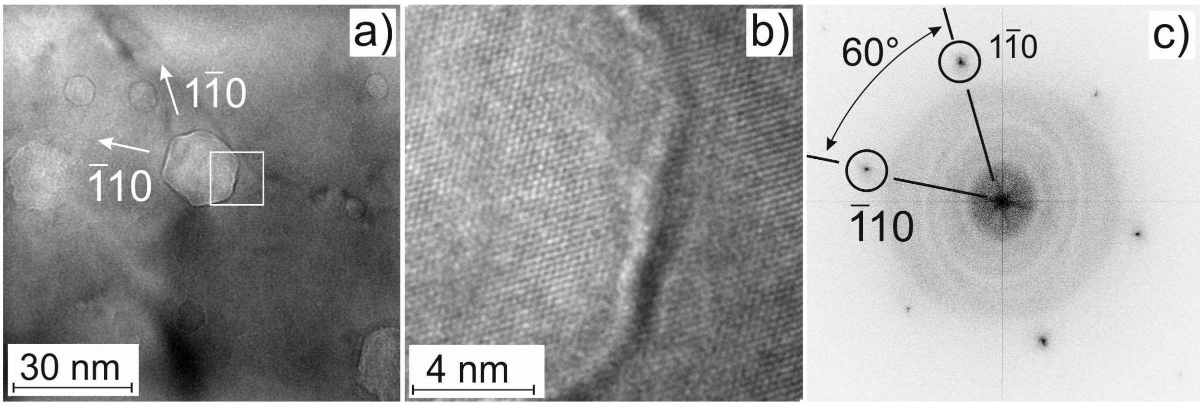

Fig. 3: HRTEM image of a cavity in alloy 2 irradiated at 350°C (a) and fast Fourier transformation image showing crystallographic orientation (b).