Effect of high-energy heavy ion irradiation on the nanoscale state of promising titanium alloys and ODS steel*

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The most promising functional materials for operation under high-energy and high intensity particle beams are complex heterogeneous systems strengthened by nanoscale inclusions and phases. Energy losses in such structures are nontrivial and can contribute to local changes in the structural-phase state of the material. Objects of this study are two titanium alloys (Ti-5Al-4V-2Zr and Ti-6Al-4V) and oxide dispersion strengthened steel ODS Eurofer steel.

The effect of room temperature irradiation on the microstructure was studied by high-resolution transmission electron microscopy (TEM) with energy-dispersive spectroscopy. Cross-section and usual TEM samples of the pristine and irradiated state of the materials were produced by means of focused ion beam and electrochemical thinning.

Irradiation of titanium alloys

Two types of titanium alloys were irradiated at the GSI UNILAC with Au ions (4.8 MeV/nucleon, up to 1×10^{13} ions/cm^{-2}). The microstructure of this widely used Ti-6Al-4V is formed by large (~30 μm) nearly equiaxial α-phase grains enriched with Al and decorated at their boundaries with V-rich β-phase inclusions. Ti-5Al-4V-2Zr alloy shows a bimodal grain distribution: packets of elongated α-phase grains separated by β-phase columns (so called basket-wave microstructure).

Irradiations with swift Au ions led to the formation of structural defects observed as a black dots aligned along the irradiation direction. Their average size is estimated to be 2±1 nm (Figure 1). These features seem to be partially coherent with the matrix. It is assumed that they may serve as nucleation sites of intra-granular β-phase precipitates. TEM EDXS analysis showed that the chemical composition of both α and β phases, as well as the spatial distribution of the grains remain stable under irradiation.

An earlier investigation of the microstructure of the Ti-5Al-4V-2Zr alloy after irradiation with low-energy (101 keV/nucleon) titanium ions at 260 °C revealed a high concentration of dislocation loops in the irradiated region of the sample. Tomographic atom probe analysis (APT) of the local chemical composition of the irradiated sample showed the formation of nanoscale vanadium pre-precipitates in the α-phase of the alloy.

Irradiation of ODS Eurofer

Irradiations of ODS Eurofer with 4.8 MeV/nucleon Au ions (1×10^{11} and 5×10^{12} cm^{-2}) and 1.2 MeV/nucleon Xe ions (1×10^{13} and 1×10^{14} cm^{-2}) led to the formation of amorphous areas within large (>8 nm) oxide particles. These features are probably tracks produced along the ion paths. Our finding is consistent with the results of previous studies of the effect of high-energy radiation on the nanostructure of ODS steel [2]. The average size of the observed tracks is 3±1 nm. Their number density correlates with the applied ion fluence. An amorphous transition layer was observed at the interface of large oxide particles after irradiation with 4.8 MeV/nucleon Au ions.

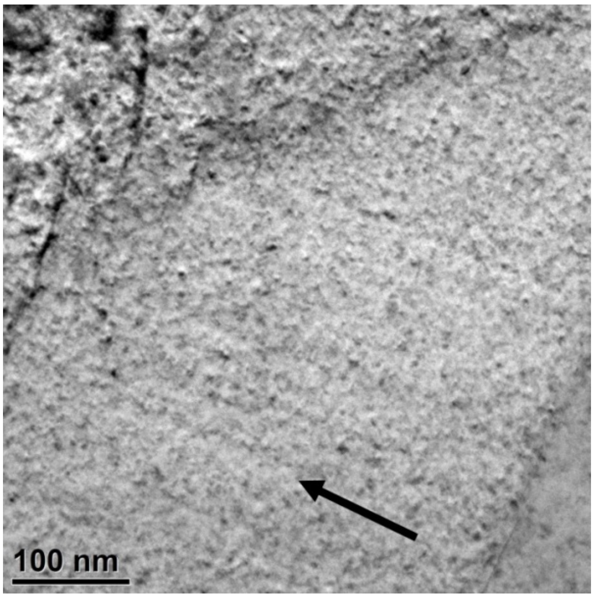

Figure 1: Representative bright-field TEM image of Ti-6Al-4V alloy irradiated with Au ions (4.8 MeV/nucleon) up to 5×10^{12} cm^{-2} at room temperature. Arrow shows irradiation direction

It has been shown that after the irradiation with low energy Fe ions (100 keV/nucleon), the number density of oxide particles increased. Also, an increase in the fraction of small-size oxides (less than 5 nm) was observed. APT analysis showed that the composition of the nanoclusters changes under irradiation. There is an exchange of chemical elements between clusters, matrix and oxide particles.

Our results provide evidence of the instability of strengthening nanoscale phases and inclusions in promising titanium alloys and ODS steels under ion irradiation.

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References

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