Irradiation effects on tensile ductility and dynamic toughness of ferritic-martensitic 7-12 Cr steels (P4-I-269)

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The superimposed effect of irradiation-induced hardening by small defects (clusters, dislocation loops) and chromium-rich `-precipitate formations on tensile ductility and Charpy-impact behaviour of various ferritic-martensitic (7-13)CrWVTa(Ti)-RAFM steels have been examined by micro-mechanical deformation and ductile/dynamic fracture models. Analytical relations have been deduced describing irradiation-induced changes of uniform ductility and fracture strain as well as ductile-to-brittle transition temperature DBTT and ductile upper shelf energy USE observed from impact tests. The models apply work-hardening with competitive action of relevant dislocation multiplication and annihilation reactions. The impact model takes into account stress intensity with local plasticity and fracture within the damage zone of main crack. Especially, the influences of radiation-induced changes in ductile and dynamic fracture stresses have been considered together with effects from strain rate sensitivity of strength 0  m=lny/ln` 1, `- precipitate morphology as mean size dp and volume fraction fv as well as deformation temperature and strain rate `. For these, particularly the correlation between tensile ductility and impact properties have been examined.

Strengthening by clusters and loops generally reduces uniform ductility, and more stronger fracture strain as well as ductile upper shelf energy USE and additionally increases DBTT for constant fracture stresses. A superimposed precipitation hardening by `- formation of dp3-6 nm, fv<0.01 as especially observed in higher chromium containing 10-12Cr steels at higher irradiation doses strongly reduces further fracture strain and toughness USE and increases DBTT. However, uniform ductility is increased more pronounced at an optimum particle size dp* which remains independent on strain rate sensitivity m. This optimum dp*>6 nm, which clear above the shearable limit of coherent `-precipitates increases with increasing fraction fv and but strongly reduces with increasing matrix strength due to full martensitic structure, higher C, N alloying contents and pronounced hardening by irradiation-induced cluster and loop formations. A combined increase of fracture stresses due to irradiation-induced changes of the grain boundary structure diminishes the strength-induced increase in DBTT and more stronger the reduction of toughness USE. As the model-assisted analyse of data observed on various RAFM steels at 60 dpa have shown, the comparably weaker normalised toughness reductions U=USE/USEo at lower irradiation temperatures of TI100–300°C are caused mainly by strain-induced fracture appearance. The superimposed `- formation in 10-12CrMoVNb steels strongly increases DBTT and particularly also the normalised toughness reduction U due to pronounced work hardening in connection with evident reductions of ductile and dynamic fracture stresses. The DBTT generally increases with decreasing uniform ductility more stronger at smaller `- precipitate sizes and weaker initial hardening. Dynamic toughness USE otherwise increases with increasing fracture strain and uniform ductility indicating that these are qualitative similar properties. The obtained analytical and numerical results are especially used for analyses of experimental results of ductility and Charpy-impact properties obtained from 10-12CrMoVNb and (7-9)CrWVTa(Ti)-RAFM steels including Eurofer`97 below 60 dpa at TI=100-500°C. Additionally, the possible methods for extrapolating ductility and toughness data to high doses will be considered including the effect of oxide dispersion hardening in ODS-RAFM steels.