Mechanisms of Degradation and Brittle Fracture of Reactor Pressure Vessel Steels Under Longterm Operation

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Degradation of reactor pressure vessel (RPV) steels mechanical properties (that appears in ductile-to-brittle transition temperature shift) is mostly determined by their structure degradation. Changes in mechanical properties of the BCC-lattice steels under long-term operation are stipulated by action of two mechanisms: the hardening one (radiation hardening due to the formation of radiation defects and radiation-induced precipitates) and non-hardening one (formation of intragranular and intergranular segregations of impurities – the known phenomenon of reversible temper brittleness).

TEM and fractographic studies of the samples of VVER reactor pressure vessels steel were carried out.

The dependence of radiation-induced structure changes and the share of brittle intergranular component in the fracture surfaces of Charpy specimens on the chemical composition, test temperature and irradiation dose (fast neutron fluence) was studied. The correlation between the increase of the yield stress and the density of radiation defects and radiation-induced precipitates depending on the fast neutron fluence was set. Moreover it was shown that there is a temperature dependence of the share of brittle intergranular component: this value increases from the lower shelf on the KCV curve, reaches a maximum in the temperature range of ductile-brittle transition, and decreases to zero on approaching the upper shelf. The presence of large columnar grains in weld metal is shown to promote the phosphorus concentration at grain boundaries, which results in increasing of the share of brittle intergranular fracture.

Apparently, the growth of the share of intergranular fracture with the temperature rising is associated with an increase in concentration of microcracks nucleation sites by increasing the concentration of slip lines.

According to the results of fractographic studies the dependence of the share of brittle intergranular fracture on three parameters: nickel content in steel (for a given phosphorus content), time of isothermal exposure at RPV operating temperature and fast neutron fluence was plotted.

It was established that the share of brittle intergranular fracture increases with the fast neutron fluence, thermal exposure time and nickel concentration. Moreover, we showed that the share of this structural component in the fractures of irradiated Charpy specimens is higher than in similar samples subjected to the equivalent time of exposure to operating temperatures, but without irradiation.

Increasing of the exposure time at the operating temperatures was found to enhance segregation processes, and increasing of the radiation dose, in addition, increases the density of radiation-induced nanoscale precipitates, ie, radiation hardening. Effect of nickel on the share of brittle intergranular fracture is both embrittlement strengthening due to the formation of grain boundary impurities segregations and yield stress increasing due to the formation of radiation-induced nanoscale precipitates on nickel basis.