§2. Impact Properties of Low Activation Vanadium Alloy after Low-temperature Newtron Irradiation at 450 °C and Below

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Vanadium alloys are very attractive option for structural materials for DEMO and commercial fusion reactors. Operation temperature for vanadium alloys has been limited to 400~450°C, from ductile-to-brittle transition temperature (DBTT) shift due to irradiation hardening during neutron irradiation around 10 dpa (displacement per atom) or more. It would be possible to extend the limit toward lower temperature, if irradiation dose is limited, or resistance to irradiation embrittlement is improved for vanadium alloys. The extension of the operation temperature range leads not only to larger temperature gradient in fusion blanket and thus higher thermal efficiency, but also to application to the other devices and reactors. Considering irradiation condition of test blanket module (TBM) for International Thermonuclear Experimental Rector (ITER), operation temperature is expected above 450 °C, while that of shielding blanket is estimated as 100-140 °C. TBM is potentially irradiated at similar temperature to the shielding blanket except TBM test operation time. On the other hand, typical operation temperature ranges 350~550 °C and 100~300 °C for fast breeder reactor (FBR) and light water reactor (LWR), respectively. The purpose of the present study is to estimate and to discuss the resistance of vanadium alloy to irradiation embrittlement at 450°C and below, from its impact properties.

A reference low-activation V-4Cr-4Ti alloy, NIFS-HEAT-2, was irradiated in JMTR, JOYO, HFIR and BR-II nuclear rectors. After the irradiation, Charpy impact tests were carried out with Charpy V-notch specimens.

Figure 1 plots absorbed energy in the Charpy impact tests at various test temperature. The energy is normalized by the specimen width (B = 1.5 mm) and the ligament size (b = 1.2 mm). In the present study, ductile-to-brittle transition temperature (DBTT) is defined as the temperature, where absorbed energy is 0.2 J mm^{-3}, which is half the upper-shelf energy, 0.4 J mm^{-3} before irradiation. DBTT before irradiation, the one after irradiation up to 0.08 dpa at 290 °C and up to 3.7 dpa at 430 °C were below liquid nitrogen temperature, -196 °C. DBTTs were -144, -139, -89, -85 °C for the irradiation conditions of 0.38 dpa at 60 °C, 0.98 dpa at 400 °C, 0.11 dpa at 400 °C, and 8.5 dpa at 450 °C, respectively. The relationship between irradiation temperature and DBTT is shown in Fig. 2. Correlation between DBTT and irradiation temperature was not clear, therefore DBTT was plotted again with hardness after irradiation in Fig. 3. DBTT after irradiation was increased with increasing hardness after irradiation except for the irradiation condition of 0.11 dpa at 400 °C (JMTR, He).

According to microstructural analyses with a transmission electron microscope, the irradiation hardening was induced by formation of dislocation loops, dislocation tangles and irradiation-induced precipitates. Generally, larger irradiation hardening induces larger DBTT shift for vanadium alloys. However, the relationship between DBTT and hardness for 0.11 dpa at 400 °C was irregular, compared with the trend line in Fig. 3. This irregular behavior might be attributed to the coarsening of the irradiation-induced precipitates up to 100 nm, which was much larger than ~5 nm in the other conditions. Larger precipitates could enhance brittle fracture by crack initiation and propagation on them.

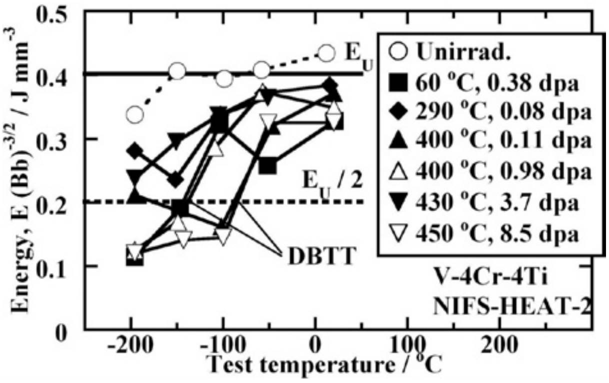

Fig. 1 Absorbed energy in the Charpy impact tests. Irradiation temperature and dose are indicated in the symbol captions.

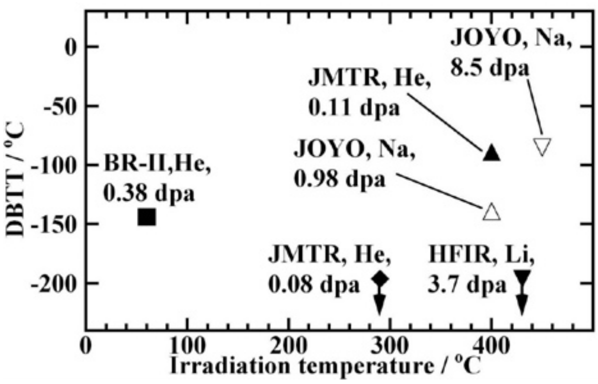

Fig. 2 Relationship between DBTT in the impact tests and irradiation temperature. Nuclear reactor used and irradiation atmosphere are also indicated.

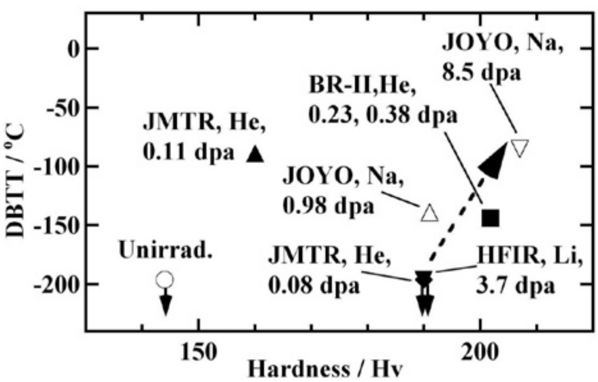

Fig. 3 Relationship between DBTT in the impact tests and hardness. For BR-II irradiation, DBTT and hardness was measured with the specimens with a dose of 0.38 and 0.23 dpa, respectively.