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Status and the challenge of Japanese materials property handbook to facilitate structural design criteria for DEMO in-vessel components

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This paper aims to provide the first release of Japanese materials property handbook (MPH) for structural design of DEMO, specifically addressing on F82H as Japanese reduced-activation ferritic/martensitic (RAFM) steel. In parallel, the issues and challenges to facilitate the structural design criteria (SDC) to meet requirements of DEMO specific environments, e.g., multi-axial loading, high-temperature water corrosion, and 14 MeV neutron irradiation, are summarized as key outcomes of BA phase-I activity ended in March 2020.

(1) Introduction
Various parts and assemblies of DEMO in-vessel components, which are composed of various fusion materials such as RAFM, refractory tungsten metal, cupper alloys etc., should demonstrate their structural conformity during not only normal but also accidental conditions. At the check and review point in Japan to judge to move to an engineering design phase of DEMO in middle 2020s, completeness of the conceptual design of DEMO should be provided without any experimental validation under DT fusion environments. Alternatively, we have to establish the reasonable methodology, i.e., SDC specific for DEMO in-vessel components, to qualify the design. For that purpose, due to somehow lack of materials data under the practical fusion environments, fission reactor irradiation data and prediction by simulation are essential. Tanigawa et al. therefore proposed to explore the way to adopt the limit state design, which is based on reliability engineering, as one possible solution to design practical components [1, 2]. In this approach, materials strength standards need to be established with statistically sufficient number of data including neutron irradiation data.

(2) Status of F82H materials property handbook
The Japanese RAFM, F82H (Fe-8Cr-2W, V, Ta), is considered as the leading candidate material for structural components of both DEMO blanket and divertor systems and with various areas of R&D non-irradiated/irradiated behavior was summarized so far [2, 3]. With abundant database of F82H, the material property handbook of RAFM has been developed. In particular, time-independent materials strength standards (Fig. 1) are determined by referring French design and construction rules, RCC-MRx. In addition, time-dependent properties such as fatigue and creep rules were specified. It is finally achieved that the non-irradiated strength data including physical properties, which have already been provided in [4], are now available as initial inputs for the DEMO in-vessel component design.

In parallel, we have started the assessment of materials strength standards for irradiated F82H with completion of initial sets of high-dose bench-mark neutron irradiation aiming at 80 dpa, which was performed under the Japan-US collaboration utilizing the High-Flux Isotope Reactor (HFIR) in ORNL. Specifically, tensile results at 300℃ as the lower temperature limit of the design were first obtained for irradiated F82H (dose = 80 dpa Tirr = 300℃). It is noteworthy that precise strain measurement was first achieved by adopting non-contact digital image correlation for miniature specimens, the fundamental technique of which is being assessed in IAEA coordinated research project (CRP) to establish the general guideline of the small specimen test techniques (SSTTs) for fusion materials.

Figure 2 summarizes the evaluation results of the status and issues of F82H MPH by adopting the attribute guides. More efforts are now addressed on new irradiation tests to increase statistical data with a target dose of ~20 dpa for the engineering design of DEMO and a complete set of MPH is planned with validation by 14 MeV neutron irradiation in 2030s. The challenge of the 14 MeV neutron irradiation is mostly found in irradiation techniques, e.g., control of irradiation dose and temperature, as well as capability of remote-handling test techniques using SSTT. In near-term, it is required to find out the color code of "white (blank)"items, which cannot be categorized due to lack of data for judgement, to recognize and remove potential show stoppers in early stage.

(3) Issues and challenges to facilitate structural design criteria for DEMO
The fusion blanket system is suffered from steady-state stresses during normal operation, e.g., thermal stress, Maxwell stress and irradiation-induced stresses, while instantaneous Lorenz stress at disruption. Moreover, transient loading conditions, e.g., thermal fatigue due to startup and shutdown, and their mixture, e.g., fatigue-creep, need to be considered. From these aspects, it is undoubted that a reasonable and comprehensive structural design rule to consider multi-axial loading conditions need to be established to meet various DEMO scenarios. With completion of BA phase-I activity, capability of the modified universal slopes equation for

estimation of multi-axial fatigue was demonstrated. By contrast, it was also found that the fatigue lifetime under the high-temperature (300℃) and high-pressure (15.5 MPa) water with dissolved oxygen of <5 ppb, as one of assumed DEMO water chemistry of both blanket and divertor coolant, was considerably decreased (1/19 of that obtained in air) [5]. These lifetime issues will be considered in the design to establish the design criteria.

More importantly, irradiation-induced embrittlement coupled with loss of ductility is the most critical issue in case of structural design of DEMO in-vessel components, which are subject to heavy neutron irradiation. To explore a probable solution, the Weibull stress criterion has been considered. Analytical method based on the Weibull stress criterion, which is also being assessed under the IAEA CRP, was preliminary applied to estimate the brittle fracture behavior for large structural components from small coupon toughness specimens assuming in-box LOCA of the blanket [6]. The challenge is validation to adopt the case of multi-axial loading and this will be discussed in this paper.

These issues are more addressed on structural discontinuity such as joining parts and capability of DEMO fabrication technologies needs to be well-assessed. Especially, failure mode and failure cause for each component should be evaluated based on the assumed DEMO operation scenarios. BA Phase-II project starts from 2020 between JA and EU. The initial results of the assessment will be discussed in this paper, providing practical research plans to realize early DEMO engineering design activities.

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