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Technical challenges on material and design criteria development for fusion in-vessel components

Hiroyasu Tanigawa

Rokkasho Fusion Institute, National Institutes for Quantum and Radiological Science and Technology, Aomori, Japan

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ABSTRACT

Preparation of irradiation database is essential for the design activity of fusion reactor in-vessel components since it is difficult to suppress the irradiation-induced degradation of material properties within the negligible level. On the other hand, the preparation of irradiation database corresponding to the real fusion in-vessel environment in the level that the existing design codes require for new material is not realistic. This limitation is due to the limited capability of irradiation experiments, and the fusion neutron irradiation environment is not available for the next ten years. The probability-based design method could be a potential alternative approach to evaluating the possibility of components' failure, where the material property is defined with a probability density function. The statistical analyses of data are required to provide the function, and a case study on as prepared and post-irradiation tensile properties of Japanese reduced activation ferritic/martensitic steel F82H was conducted. It was indicated that the most data show a normal distribution, but post-irradiation elongation data shows a possibility to follow a Weibull distribution.

1. Introduction

It is well recognized that fusion in-vessel components will suffer from a significant 14 MeV DT fusion neutron irradiation, along with high heat flux and particle (He) bombardment under high magnetic field up to 10T. The structural material development for those fusion in-vessel components, such as breeding blanket, was regarded as the most challenging technical issue because of the significance of fusion neutron irradiation, which induces high displacement damages with a significant amount of the transmutation formed gas elements such as Helium and Hydrogen. After the decades of efforts, it becomes clear that it is not realistic to suppose the development of a structural material which will not show any significant degradation due to irradiation. But it might be able to shift the irradiation condition at which the degradation becomes not negligible or unacceptable, which define the lifetime of the material (and the components as a consequence).

Thus, it is essential to have a fusion DEMO reactor design criteria for in-vessel components (DDC-IC) which define the negligible or acceptable level of irradiation-induced degradation of properties to ensure the structural integrity which was required to have safety strategy and expected function intact. There is a design code for ITER shield blanket which considers irradiation effects (SDC-IC). But this is not applicable for fusion DEMO reactor in-vessel components because the limit was defined only for austenitic stainless steel up to the level where the existing design code is applicable, and this will limit the irradiation dose below a few dpa.

The difficulty over the development of structural material and fusion DDC-IC lies on the fact that these cannot be developed "empirically", which is the way that the existing design code has developed, until we construct DEMO itself. Thus, we have to develop DDC-IC "without" any operation experience under the 14 MeV DT fusion operating environment up to the expected high irradiation dose level.

Therefore, the most significant technical challenge is that to develop a reasonable (acceptable) fusion DDC-IC, and to develop and qualify a material corresponding to the DDC-IC, "theoretically", based on the knowledge and data acquired by DD plasma operation, fission neutron irradiation and various simulation irradiation experiments, and modeling/simulation calculations. The fusion neutron irradiation facility, such as International Fusion Material Irradiation Facility (IFMIF) or early fusion neutron source under planning in Japan or EU, is expected to be constructed to establish fusion neutron irradiation database. Unfortunately, those will not be available for ten years at least, and even it becomes available, it will take time to accomplish a vast irradiation matrix since those irradiation capabilities are quite limited to complete high dose irradiation. Thus, the strategy to mitigate the lack of empirical data should be provided to prepare DDC-IC and material database to make it possible to initiate construction DEMO as soon as we see the successful operation of ITER DT operation.

In this paper, the possibility to apply the probability based design method as a potential design methodology of fusion in-vessel

E-mail address: tanigawa.hiroyasu@qst.go.jp.

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components was discussed, focusing on the requirement to material qualification and database. The statistical analyses on the tensile data of as prepared and post-irradiation properties of Japanese reduced activation ferritic/martensitic steel, F82H, was attempted to discuss a technical issue on providing a material database for the design activity.

2. The probability-based design method

The most existing design code is based on the deterministic design method. In this method, the minimum material strength is firstly defined according to the material standardization; then allowable stress is defined by dividing minimum material strength by the factor of safety. The characteristic load of the components is designed not to exceed the defined allowable stress. The issue is that the factor of safety is the number which has been defined empirically, and the degradation of material property is not allowed or conservatively limited. It is very difficult to define the factor mentioned above for fusion in-vessel components and its structural material since "empirical" approach under actual high neutron dose environment is not feasible until DEMO operation, and it is not realistic to define degraded properties due to 14 MeV fusion neutron irradiation.

The probability-based design method is the design method which has been developed for civil engineering to calculate the probability of failure considering a variety of materials (metal, soil, or concrete) under indeterministic loading condition [1]. The basic concept of calculating the probability of failure itself had been developed as the core concept of reliability engineering, and now it is considered in the nuclear plant [2], and fast breeder reactor design code as a part of "system based code" [3–5]. In this method, the probability of failure P is calculated based on the probability density function of postulated load distribution f_s (s) and material property distribution f_R(r)

$$P = \int_0^\infty f_S(s)\left[\int_0^s f_R(r)dr\right]ds = \int_0^\infty f_S(s)\cdot F_R(s)ds,$$

where F_R(s) is distribution function of material property in case the load "S" is applied. In this calculation, the factor of safety does not involve. In case of fusion in-vessel components, f_s (s) can be estimated based on the plasma operation scenario and component design. F_R(s) can also be estimated based on the statistical inference on material properties. In case there are an irradiation-induced material property changes, the probability density function of material property distribution after irradiation will be described as,

$$f_R^{irrad.}(r) = f_R(r - \Delta r(D)) \times f^*(r, D),$$

where D is irradiation dose, Δr (D) is estimated changes of property, and f*(r, D) is the modulus function which describe the probability density changes due to irradiation (Fig. 1). The benefits of the probability based design method are that there is no need to define the factor of safety, and the probability of failure is given by a number which includes the ambiguity of material property due to the lack of data number, and easily correspond to the design or material changes,

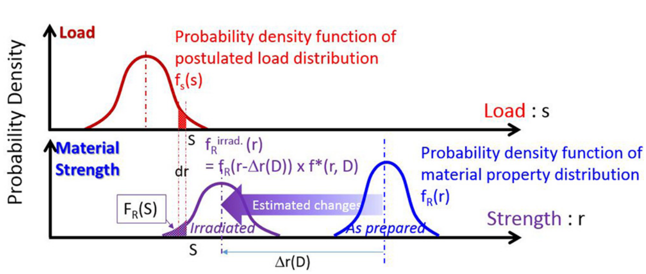

Fig. 1. The schematic drawing of the concept of the probability based design method with a probability density functions of load and material property distribution of as prepared and after irradiation.

or upgrade of data itself.

Thus, it is essential to conduct statistical analyses on material property data to make the data applicable to the probability based design method. In the following section, the statistical analyses of F82H tensile properties are demonstrated.

3. The statistical analyses of F82H tensile properties

3.1. Procedure

Materials used for the analyses is F82H (Fe-8Cr-2W-0.2 V, Ta). The tensile data obtained from 7 heats of F82H in the product form of various thickness of plates tested at room temperature, 300, 400, and 500 °C were used for as prepared F82H data analyses. In case of irradiated data analyses, 300 °C fission neutron irradiated and 300 °C tested tensile data of F82H-IEA heat (Fe-0.09C-7.7Cr-1.95W-0.16Mn-0.16V-0.02Ta-0.006N) was analyzed. ± 10% of the variation in irradiation dose and temperature is considered to be an equivalent irradiation condition.

The analytical procedure is as follow.

1) Rank each data in order at each temperature (and irradiation dose in case of postirradiation data).

2) Normalize data by dividing each data with the value acquired by averaged property − temperature equation (or averaged data for the case of postirradiation data)

3) Give the cumulative probability based on the median rank cumulative probability of i^{th} data out of total data number "n" in an approximate expression given by

$$P(n, i) = (i - 0.3)/(n + 0.4)$$

4) Analyze the normalized average (μ), standard deviation (σ), standard error (95%CI: confidential interval) assuming a normal distribution, and Weibull (shape) parameter (*m*), scale parameter (η) assuming a Weibull distribution.

5) Calculate correlation coefficient (*CC*) between median rank cumulative probability and calculated probability assuming a normal distribution (Nor.) or Weibull distribution (W) using analyzed parameters.

6) Judge the distribution and define property distribution function F_R(x, T). If the data distribution is a normal distribution, it will be described as

$$F_R^{Nor.}(x) = 0.5 \times \left\{1 + erf\left(\frac{x-\mu}{\sqrt{2}\cdot\sigma}\right)\right\},$$

where x is a variable corresponds to the normalized property data, and *erf*(X) is an error function

If the data distribution tuned out to be a Weibull distribution, the property distribution function will be,

$$F_R^{W}(x) = 1 - exp\{1 - (x/\eta)^m\}$$

3.2. The analytical results on as prepared tensile properties

3.2.1. 0.2% proof stress

The temperature dependence of 0.2% proof stress S_y of F82H can be described as,

$$S_{y(av)} = 567.73 - 0.6274T + 2.151 \times 10^{-3}T^2 - 3.024 \times 10^{-6}T^3,$$

where T is the test temperature. All the data is normalized with the value calculated by this equation and statistically analyzed (Fig. 2, Table 1). The value of *CC* indicates that the data distribution has a tendency to follow a normal distribution, even though both *CC* values are over 90% (0.90). The cumulative probability dependence shows some difference over the average (μ = 1.0), but it can be described with a single function by ignoring the offset observed in higher value as it is