THE STRATEGY OF FUSION DEMO IN-VESSEL STRUCTURAL MATERIAL DEVELOPMENT

H. TANIGAWA
National Institutes for Quantum and Radiological Science and Technology
Rokkasho, Aomori, Japan
Email: tanigawa.hiroyasu@qst.go.jp

E. DIEGELE[1], Y. KATOH[2], T. NOZAWA[3], T. HIROSE[3], M. GORLEY[4], H. SAKASEGAWA[3],
E. GAGANIDZE[5], J. AKTAA[5], G. PINTSUK[6]
[1] EUROfusion Consortium, Programme Management Unit, Garching, Germany
[2] Oak Ridge National Laboratory, Oak Ridge TN, U.S.A.
[3] National Institutes for Quantum and Radiological Science and Technology, Aomori, Japan
[4] UK Atomic Energy Authority, Culham Science Centre, Oxfordshire, UK
[5] Karlsruhe Institute of Technology, Institute for Applied Materials, Eggenstein-Leopoldshafen, Germany
[6] Forschungszentrum Jülich, Institute for Energy and Climate Reserach – Plasmaphysics, Jülich, Germany

Abstract

The strategy of fusion in-vessel structural material development toward fusion DEMO is addressed with special emphasis on the current status and the limitations related to the reliability of data. A major issue in developing and validating structural materials for a fusion DEMO reactor are lack of facilities where materials can be tested under the real in-vessel conditions of deuterium-tritium (DT) fusion. Therefore, the most significant technical challenges are to develop and qualify materials based on the knowledge and data acquired by fission neutron irradiation and various simulation irradiation experiments and to develop and verify a framework of DEMO reactor design criteria for in-vessel components (DDC-IC). A new strategy is proposed based on probabilistic approaches as a part of the design methodology in order to mitigate the uncertainties caused by multiple sources.

1. INTRODUCTION

The structural material development for the Fusion DEMO in-vessel structure, such as breeding blanket, is regarded as the most challenging technical issue due to the significance of 14 MeV DT fusion neutron irradiation that induces high displacement damage and transmutations generating significant amounts of gas elements such as helium and hydrogen. Various efforts have been conducted for decades to identify and understand 14MeV neutron irradiation effects on the materials, and to develop a material insensitive to irradiation effects. In design point of view, it was expected to develop a material which shows irradiation induced property degradation within an allowable range being defined in the material standard, and dimensional stability such as a small swelling below 3%, equivalent to 1% permanent deformation, under high dose irradiation. This might be achievable for the irradiation dose level of ITER or early DEMO, but it would be difficult for high dose level applications since nuclear transmutations of major elements is unavoidable which could induce degradation of properties (physical and mechanical) under the harsh environmental condition. Thus, it is essential to define the allowable degradation levels of properties due to irradiation, which is expected to be defined in fusion DEMO reactor design criteria for in-vessel components (DDC-IC).

The challenges to develop a suitable structural material and fusion DDC-IC are that these cannot be developed "empirically" until DEMO itself is in full power operation. The objective of this paper is to overview the status and identify the issues of the current strategy based on deterministic approaches and to propose a new strategy based on probabilistic approaches as a part of the design methodology in order to mitigate the uncertainties caused by multiple sources.

2. THE CURRENT STRATEGY AND ISSUES

The most commonly used design code based on the deterministic approach is the allowable stress design method. In this method, the plastic collapse is the target fracture mode to prevent, and the characteristic load of the components is designed not to exceed the defined allowable stress. This allowable stress is given by dividing minimum material strength, which is defined in the material standard, by the pre-defined factor of safety. The issue in this approach is that this factor of safety is an empirically defined number, and the degradation of material property is not allowed or conservatively limited.

The strategy is to develop materials which show a “minimum” change in properties as well as good dimensional stability under neutron irradiation within a “maximum design space”. Also, it needs to address ductility and strength, fracture toughness and resistance under creep and fatigue. Ideally, neutron irradiation induced changes are expected to be negligible or “minor”. Ferritic/martensitic steels are regarded as the most promising blanket structural material since they show a very low swelling rate compared to that of stainless steels. Reduced-activation ferritic/martensitic (RAFM) steels, such as F82H (Fe-8Cr-2W-0.2V-0.04Ta) or EUROFER-97 (Fe-9Cr-1W-0.2V-0.12Ta), have been developed and their technical feasibilities are demonstrated [1]. The developments of high sink strength materials, such as oxide dispersion strength (ODS) steels or nano-featured ferritic alloys (NFA), castable nano-strcutured alloys (CNA), or the high-temperature materials, such as SiC/SiC composites, are regarded as “advanced material” development which leads the edge of this strategy [2].

The reality is, however, that irradiation effects are neither “negligible” nor “minor”. They limit service life and performance. Therefore, it is essential to define the negligible and maximum level of irradiation-induced changes which could be incorporated into safety factors that are defined “empirically”. This approach is available in frameworks such as in the Afcen RCC-MRx design and construction code developed for sodium-cooled fast reactors, etc. or in ITER Structural Design Criteria for in-vessel components (SDC-IC).

One of the significant issues concerning irradiation effects is the ductility degradation. The typical irradiation effects on RAFM mechanical properties are hardening and embrittlement, but the loss of uniform elongation and decrease in total elongation is also significant in RAFM steels. In the design criteria, a structural material is assumed to behave as an elastic-perfect-plastic material, but a certain level of ductility and plastic hardenability is presupposed by requiring to achieve a certain level of yield ratio and elongation. This presupposition makes it possible not only to secure the structural integrity at the high-stress concentrated region of structurally or microstructurally discontinuous parts during a variety of transient and rapid changes of loading conditions but also to ignore the impacts of undetectable size defects or flaw. Thus, it will be required to define the limit to the local plastic strain in order to prevent local fracture due to the loss of ductility induced by local plastic flow and high triaxiality of the stress field or irradiation. Such limits are investigated for stainless steel [3], but need to be investigated for the case of RAFM steels.

Another major challenge is to provide rules, guidelines and properties from data acquired in experiments not performed under “real” fusion environment but rather from fission neutron irradiation and various simulation irradiation experiments such as accelerated ion irradiation experiments. This “integrated modeling approach” guides to determining “preliminary limits on allowable loads” data for anticipated DEMO operation scenarios and “the critical irradiation dose” up to which the fission neutron irradiation data can be postulated as the equivalent data to that of fusion neutron irradiation data [1]. It is essential that in an “integrated modeling approach” the theoretical modeling and simulations finally have to be experimentally validated by fusion neutron irradiation experiments [4].

3. A NEW STRATEGY

It is a well-known fact that the material property data show a certain level of dispersion, mainly due to the inhomogeneity of materials in a batch or between batches. The material standard is defined to minimize this ambiguity, and minimum strength, for example, is defined with a 95% confidence interval based on a statistically qualified amount of data. Irradiation data, on the other hand, are currently very limited in their size (typically n=1~3 per irradiation condition), and their statistical quality is poor compared to that of unirradiated data especially at high irradiation dose condition. Various uncertainties are expected in irradiation data mining as well as design methodologies, the DDC-IC need probabilistic approaches, where 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 the distribution function of material property in case the load “S” is applied. This calculation does not comprise the use of a factor of safety. 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. Corresponding to material property changes due to irradiation, the probability density function of material property distribution after irradiation will be described as,

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

where D is irradiation dose, Δr (D) are the estimated changes of property, and f*(r, D) is the modulus function which describes the probability density changes due to irradiation (fig. 1).

The benefits of probability based design methods are that there is no need to introduce safety factors artificially: the probability of failure then corresponds to design margins, given by numbers which include the uncertainties of material properties. The drawback, however, is that the requirement on individual components shall be very stringent to achieve an overall acceptable failure probability of the plant due to a large number of subcomponents and the difficulty in monitoring failure development in service. It is essential to conduct statistical analyses on material property data to make the data applicable to the probability based design method. Consequently, the vast amount of fission neutron irradiation data which fulfill the statistical requirements should be developed up to some "critical irradiation dose" levels at which the irradiation effects caused by fusion neutron spectra are expected to become very different from fission data [1].

In the absence of a deep experimental database, it would be challenging to define probability density functions of anticipated loads especially for plasma-near components, based on probability density functions of postulated plasma operation scenarios and their cycle-to-cycle and locally varying first wall heat fluxes. Bayesian approach is the possible approach for statistical inference to postulate the probability density function based on the limited experimental data (empirical information) [.

4. SUMMARY

The strategy of fusion in-vessel structural material development toward fusion DEMO is addressed with special emphasis on the current status and the limitations due to the reliability of data.

Importance to define the negligible and maximum level of irradiation-induced changes were indicated, which could be incorporated into safety factors under the existing design code.

It was indicated as the most significant technical challenge to develop and qualify materials based on the knowledge and data acquired in experiments not performed under "real" fusion environment but in fission neutron irradiation and various simulation irradiation experiments, and to develop and verify a framework of DEMO reactor design criteria for in-vessel components (DDC-IC).

A new strategy based on probabilistic approaches was proposed, where the probability of failure is calculated based on the probability density function of postulated load distribution and material property distribution, as a part of the design methodology in order to mitigate the uncertainties caused by multiple sources.

Critical needs to obtain the vast amount of fission neutron irradiation data which fulfill the statistical requirements were suggested up to some critical irradiation dose levels at which the irradiation effects caused by fusion neutron spectra are expected to become very different from fission data.

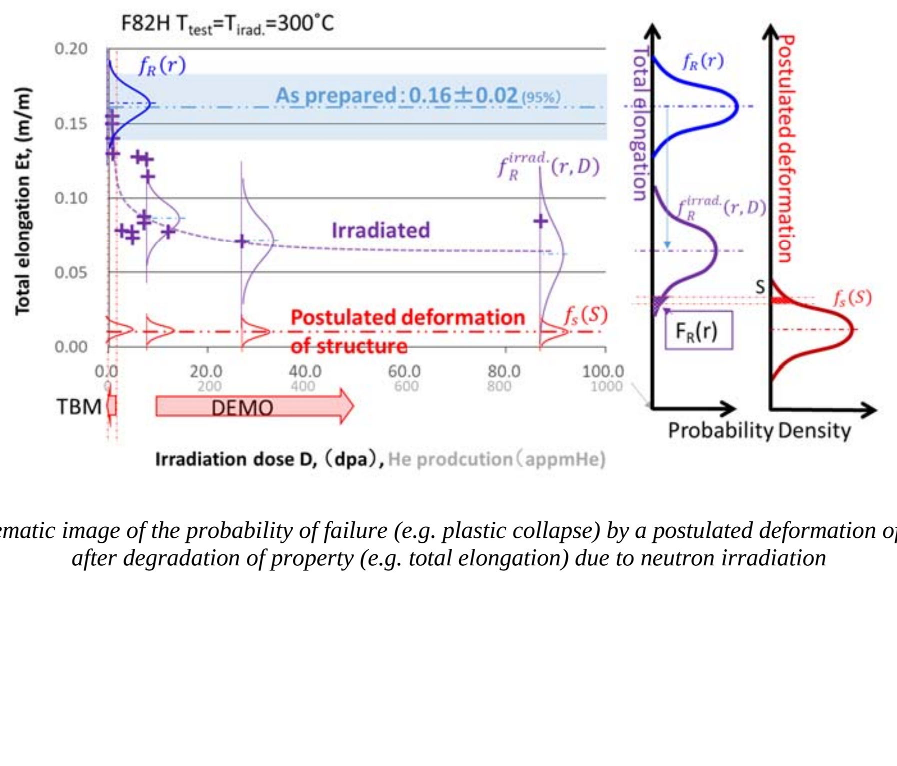

FIG.1. A schematic image of the probability of failure (e.g. plastic collapse) by a postulated deformation of the structure after degradation of property (e.g. total elongation) due to neutron irradiation

ACKNOWLEDGEMENTS

This work is supported by the Broader Approach activity under IFERC-T3PA04 and the U.S. DOE and QST collaborative project under NFE-17-06547, with UT-Battelle, LLC.

REFERENCES

[1] TANIGAWA, H., GAGANIDZE, E., et al., Nucl. Fus. **57** (2017) 092004
[2] ZINKLE, S.J., SNEAD, L.L., Annu. Rev. Mater. Res. **44** (2014) 241-267
[3] MAJUMDAR, S., SMITH, P., Fusion Eng. Des. **41** (1998) 25-30
[4] MUROGA, T., TANIGAWA, H., Fus. Sci. Tech. **72** (2017) 389-397