Proposed damage evolution model for large-scale finite element modeling of the dual coolant US-ITER TBM

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Abstract

Large-scale finite element modeling (FEM) of the US Dual Coolant Lead Lithium ITER Test Blanket Module including damage evolution is under development. A comprehensive rate-theory based radiation damage creep deformation code was integrated with the ABACUS FEM code. The advantage of this approach is that time-dependent in-reactor deformations and radiation damage can now be directly coupled with 'material properties' of FEM analyses. The coupled FEM–Creep damage model successfully simulated the simultaneous microstructure and stress evolution in small tensile test-bar structures. Applying the integrated Creep/FEM code to large structures is still computationally prohibitive. Instead, for thermo-structural analysis of the DCLL TBM structure the integrated FEM–creep damage model was used to develop true stress–strain behavior of F82H ferritic steel. Based on this integrated damage evolution-FEM approach it is proposed to use large-scale FEM analysis to identify and isolate critical stress areas for follow up analysis using detailed and fully integrated creep–FEM approach.

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1. Introduction

The US Dual Coolant Lead Lithium (DCLL) ITER Test Blanket Module (TBM) structure will be subject to complex cyclic thermo-mechanical loading [1]. Reliable performance prediction of the DCLL structure requires large-scale, 3-dimensional finite element analysis coupled with deformation damage models.

Within the framework of the VISTA (Virtual International Structural Test Assembly) project, finite element modeling of thermo-mechanical per-

formance of the DCLL TBM is being developed including rate-dependent plasticity damage functions. This approach would differ from the majority of lifetime assessments, which are based on isothermal lifetime data and the use of predictive design rules. The VISTA project aims to incorporate damage evolution models as a function of irradiation and operational time into FEM analysis of the DCLL TBM.

A dislocation-based creep damage model was developed to simulate property degradation as a result of aging and neutron irradiation. This damage model describes rate-dependent plasticity and thermal and irradiation creep of F82H. The damage model was directly coupled with the finite element

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code ABACUS and typical tension bar geometries were analyzed. Furthermore, true stress–strain curves of F82H at various temperatures 450 °C were developed.

Because of computational resource limitations, a detailed finite element analysis of the thermo-mechanical behavior of the helium cooled TBM was performed without the inclusion of the damage models. Instead, the true stress–strain behavior as predicted by the dislocation-based creep model was used. While this effort is a first step to include dislocation-based damage functions in large-scale FEM analysis, it does not fully integrate damage accumulation with FEM simulations. However, based on the successful example of using the fully integrated creep model with FEM for small test-bar samples, we propose a 'global-to-local zooming' method for the large-scale FEM analysis of the DCLL TBM structure. First, a large-scale FEM analysis would be performed to identify critical areas within the structure, to be followed by very detailed and fully coupled damage model–FEM simulation. Thus, incrementally changing material properties as a function of radiation dose and aging can be directly coupled with the FEM analysis of critical areas within any structure.

The TBM model, which was analyzed using the creep-model derived stress–strain curve included the First Wall, internal support panels, and the back-plate. The model also contains the coolant channels within each structure along with fillets and rounds between joined members of the TBM. Off-normal operation was analyzed by simulating a high pressure helium coolant leak into the DCLL TBM. It is shown that based on high-temperature ITER Structural Design Criteria [8] all primary plus secondary stress limits were satisfied.

2. Rate-dependent damage and deformation model

Extending the theory of rate processes, Ghoniem, Matthews and Amodeo (GMA) [2] were able to formulate a comprehensive theory of radiation-induced defect and dislocation microstructure evolution. Their dislocation-based creep model was initially developed to predict high-temperature deformation under arbitrary time-dependent stress and temperature histories for engineering materials. Their comprehensive dislocation creep model is based on earlier developments in creep theory [2]. The inclusion of sub-grain microstructure evolution is a key aspect of this model, as recognized earlier by Holt

[3]. This dislocation-based constitutive model is composed of six rate equations to predict the behavior of six engineering parameters, namely the creep strain, the mobile, static and boundary dislocation density, the average sub-grain radius, and the applied stress. The overall model can be summarized in the following equations [2]:

Creep strain – Orowan equation:

$$\frac{d\varepsilon^p}{dt} = b\rho_m v_g. \tag{1}$$

Mobile dislocation density:

$$\frac{\partial \rho_m}{\partial t} = v_g\left[\rho_m^{3/2} + \frac{\beta R_{sb}}{h^2} - \frac{\rho_m}{2R_{sb}} - 8\rho_m^{3/2}\left(\frac{v_{cm}}{v_g}\right) - \delta\rho_m(\rho_m + \rho_s)\right]. \tag{2}$$

Static dislocation density:

$$\frac{\partial \rho_s}{\partial t} = v_g\left[\frac{\rho_m}{2R_{sb}} - 8\frac{\rho_s}{h}\rho_m^{3/2}\left(\frac{v_{cs}}{v_g}\right) - \delta\rho_m\rho_s\right]. \tag{3}$$

Boundary dislocation density:

$$\frac{\partial \rho_b}{\partial t} = 8(1 - 2\zeta)\rho_s\frac{v_c}{h} - \left(\frac{\rho_b}{R_{sb}}\right)M_{sb}(p_s - 2\pi r_p^2 N_p\gamma_{sb}). \tag{4}$$

Average sub-grain radius:

$$\frac{dR_{sb}}{dt} = M_{sb}(p_s - 2\pi r_p^2 N_p\gamma_{sb}) - \mu\eta_v K_c R_{sb}\left[(\rho_m + \rho_s)^{1/2} - \frac{K_c}{2R_{sb}}\right]\frac{\Omega D_s}{kT}. \tag{5}$$

A constitutive relation has been added to calculate stress as a function of the total strain:

$$\frac{d\sigma}{dt} = E\left(\frac{d\varepsilon^{tot}}{dt} - b\rho_m v_g\right), \tag{6}$$

where ε^p is the creep or plastic strain, b is the Burger's vector, ρ_m, ρ_s, and ρ_b are mobile, static, and boundary dislocations density; v_g is the glide velocity, β is a density factor, R_{sb} is the sub-grain radius, v_{cm} is the mobile core glide velocity, h is the dislocation spacing within the sub-grains, v_{cs} is the static core glide velocity, p_s pressure of sub-grain growth, r_p is the mean precipitate radius, ζ is the fraction of dislocations that become part of the cell boundary, N_p is the precipitates volume concentration, γ_{sb} grain boundary energy per unit area, M_{sb} is core mobility, μ is the shear modulus, η_v is the transfer coefficient of vacancies from dislocations; K_c is a constant with a value around 10 [4], Ω is the atomic

volume, D_s is the lattice self-diffusion coefficient ($D_s = D_v C_e^v$); k is Boltzman's constant, and T is temperature.

The model is a compromise between the intense calculations of single crystal plasticity and the simplicity of the Orowan–Baily phenomenological approach. If polycrystals were to be individually modelled with crystal plasticity, the volume that can be handled with today's computers would be on the order of hundreds of cubic microns. However, the GMA creep model captures the main hardening and recovery mechanisms in an average sense, and has a dependence on the sub-grain size. In other words, grain boundary sliding contributions are ignored, with focus being directed on dislocation mechanisms, starting at the sub-grain level. It has the added attractive feature of being within the rate-theory framework, and can hence incorporate point defect and microstructure evolution equations, as well as equations for irradiation creep and swelling.

3. Implementation of damage evolution into FEM

The ABACUS FEM framework provides flexibility by enabling to couple sophisticated materials with the FEM analysis models in an integrated fashion. The GMA creep damage model was incorporated by simultaneously solving the previous set of equations with the evolution of the triaxial stress state. Sample results of this integrated approach to model standard tensile test-bars are shown in Fig. 1 for F82H steel. The figure shows the spatial distribution of Von-Mises stress, mobile, static and boundary dislocation densities, as well as the total plastic strain and the average sub-boundary radius. To our knowledge, this achievement is the first in the literature.

Fig. 2. Application of the GMA dislocation-based creep model to F82H at 450 °C (*true*: damage model; *exp*: compiled from reference [6], *Eng* (*FEA*): 3-dimensional small specimen model using ANSYS FEM code (strain (mm/mm)).
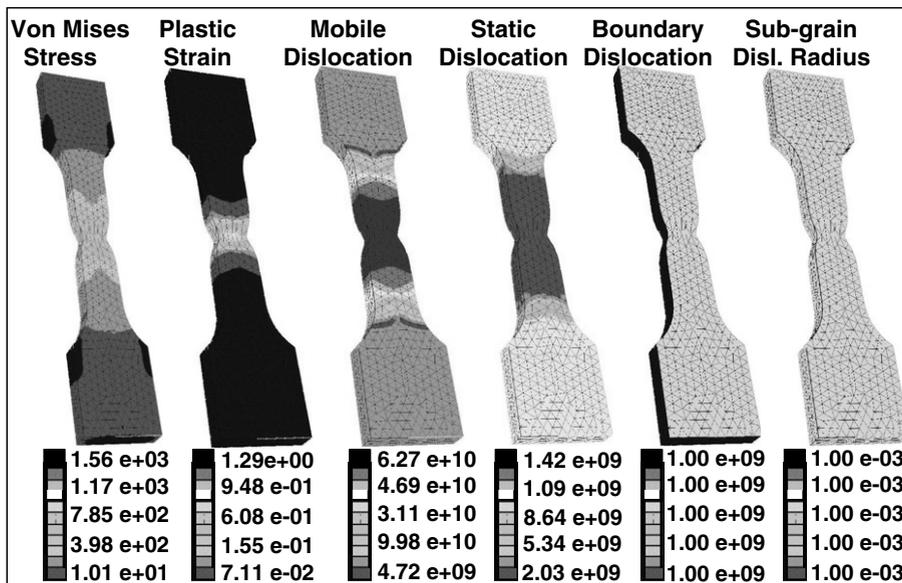
Fig. 1. Results of simultaneous stress and microstructure evolution using the fully integrated GMA dislocation-based creep model and the ABACUS FEM code (stress: MPa; strain (%); dislocation densities (cm/cm^{-3}); radius (mm)).

RIB Structure
Helium flow:
   Single Pass
   $T_{in} = 420°C$
   $T_{out} = 440°C$

FW-T_{out} = 420°C

Heat Loads:
Plasma on FW
   $q'' = 0.5$ MW/m^2
Volumetric Heating:
   $q''' = 15 \exp(-10x)$ MW/m^3
Leakage from PbLi into walls:
   10% of heat ~ 0.05

FW

5 Pass
Helium
flow

FW-T_{in} = 360°C

Heat Transfer Coefficient:
FW (plasma side only)
   $h_{coef} = 6979$ W/m^2-K
FW side rib roughened
all other surfaces assumed
smooth walls
   $h_{coef} = 3586$ W/m^2-K

FW Helium makes 5 Passes:
   Pass 1:   In 360°C → Out 372°C
   Pass 2:   In 372°C → Out 384°C
   Pass 3:   In 384°C → Out 396°C
   Pass 4:   In 396°C → Out 408°C
   Pass 5:   In 408°C → Out 420°C

Fig. 3. Solid model of a 5-pass FW-coolant flow section of the DCLL TBM showing heat loads and heat transfer coefficients used for thermal analysis FEM.

Beryllium:
$T_{max} = 590\ °C$

F82H:
$540\ °C < T_{max} < 560\ °C$
(Top ~100 μm)
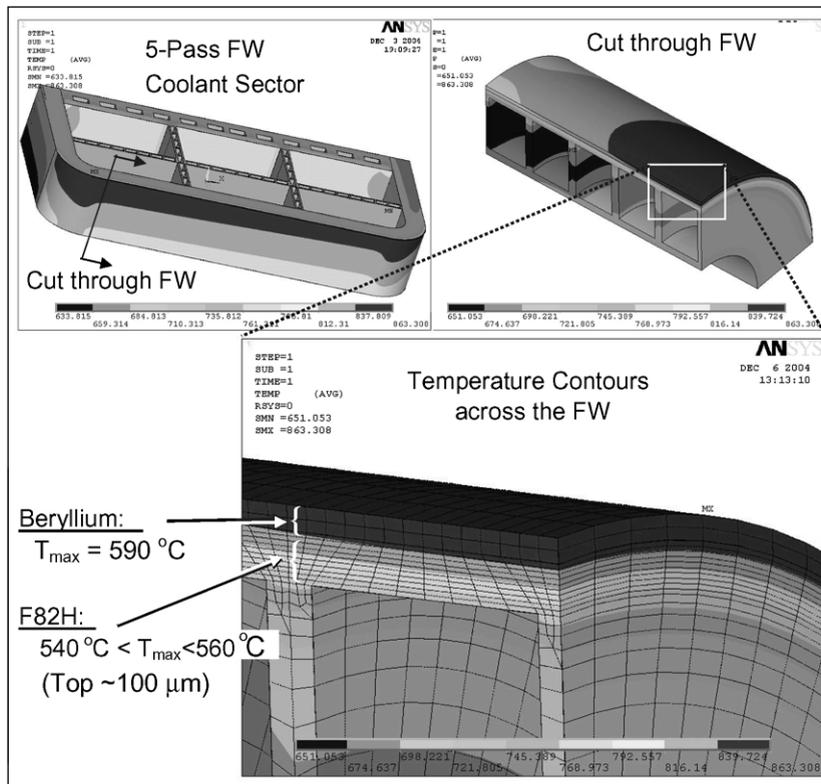
Fig. 4. Temperature contours of the DCLL TBM 5-pass FW-coolant sector.

Table 1
Summary of DCLL-5 channel section temperatures and stresses

Location	Temperature (°C)		Memb. P_m (MPa)	Primary stress intensity (MPa)		Secondary stress intensity, Q (MPa)	Primary + secondary stress intensity (MPa)	$P_L + P_b/K_t$	S_m (MPa)	S_t (MPa) 10000 h
	Average	Peak		Bending $(P_L + P_b)$	Memb. + Bending $(P_L + P_b)$					
FW	523	559	45	70	115	190	305	107	132	135
Support structure	471	477	25	45	70	157	227	65	143	179
Back plate	520	557	22	38	60	187	247	56	135	140

Primary plus secondary stress limits

Location	Average[a] temperature (°C)	Yield stress (MPa)	$X = (P_L + P_b/K_t)/S_y$	$Y = \Delta Q/S_y$	$Y = (\Delta P + \Delta Q)/S_y$
FW	523	387	0.17	0.49	0.79
Poloidal Inner support structure	471	421	0.10	0.37	0.54
Back plate	520	392	0.09	0.48	0.63

P_m general primary membrane stress intensity
P_L local primary membrane intensity
P_b primary bending stress intensity
Q secondary stress intensity
K bending shape factor
Support structure   internal poloidal support structure.
 [a] Average temperature for one plasma-on and plasma-off cycle.

Simulations of typical TBM structures using coupled GMA and FEM requires significantly more computing resources than used to modeling a small tensile test-bar. The present work is limited to using the GMA model-derived true stress–strain behavior of F82H. Fig. 2 shows the GMA based stress–strain of F82H at 450 °C. The Young's modulus, ultimate strength, and elasto-plastic tangent as predicted by the GMA–FEM model match quite well with the experimental values [5].

4. Finite element modeling of the TBM

Thermal and thermo-elastic stress analyses of the US ITER Dual Coolant Lead Lithium (DCLL) Test Blanket Module (TBM) were carried out using the finite element program ANSYS. The structural material for the DCLL is the ferritic–martensitic reduced activation F82H steel [7]. A 3-dimensional CAD model of a 5-channel section of the DCLL ITER-TBM was developed for the analysis (Fig. 3). The section is located near the top of the TBM, where the highest FW temperatures are expected. Heat conduction in the poloidal direction was considered by applying symmetry conditions, representing adjacent coolant channels above and below the section. Steady-state temperature distributions were calculated. The maximum temperatures are 559 °C and 557 °C at the FW and the Back Plate, respectively, or about 17 °C higher than the design limit of 550 °C (Fig. 4).

The corresponding stress analyses were conducted using 8-node brick elements. The average primary membrane stress was taken as the average across the plasma-facing side of the FW, and the primary bending stress was taken as ~2/3 of the peak stress based on the ITER structural design criteria definition [8]. Results show that all the primary plus secondary stress limits are satisfied within the 5-channel section of the TBM. The high-temperature ITER Structural Design Criteria provides conservative but simple rules to prevent progressive deformation (cyclic creep-ratcheting) on the basis of elastic analysis by using either the $3S_m$ or the Bree-diagram rule. These rules were applied and are summarized in Table 1. Results show that the maximum high-temperature time-independent $((P_L + P_b/K) < S_m))$ and time-dependent $((P_L + P_b/K_t) < S_t))$ design rules for, both primary membrane and membrane plus bending stresses are satisfied.

Structural analysis of the entire DCLL TBM revealed that the maximum Von-Mises stress occurs not at the FW but at the sharp interface corners between the internal support structure and the side of the FW. A preliminary steady-state structural analysis was performed and results show that with minor design modification, the DCLL design can withstand the loss of coolant accident condition without exceeding the ultimate design limit of F82H. Details are reported in Ref. [9].

5. Proposed coupling of damage function with large-scaled FEM

Until implementation of the GMA creep model with large-scale FEM analysis is computationally feasible, we propose a 'global-to-local' FEM approach. A large-scale FEM analysis would be performed without damage functions to establish 'global' stress states in the TBM and to identify critical areas. These critical or 'local' areas are then isolated for modelling using the fully integrated GMA creep model–FEM approach. The structures surrounding the localized section are replaced with appropriate boundary conditions to reflect the stress state of the entire structure.

Although, our creep model captures the main hardening and recovery mechanisms, it is still phenomenological in nature. Efforts are ongoing to resolve this aspect completely and to develop a materials damage model, which includes (1) triaxial stress states, (2) rate-independent and rate-dependent plasticity, (3) creep-fatigue deformation, (4) void-induced and grain boundary cavitation-induced damage at large strains, and (5) irradiation creep and swelling via additional rate equations for point defects and voids. Simultaneously, software development is ongoing to improve the GMA/ABACUS implementation for future large-scale FEM analysis.

6. Conclusions

A comprehensive rate-theory based radiation damage creep deformation code was incorporated with the ABACUS FEM code in an integrated fashion. The advantage of this approach is that in-reactor deformations and radiation damage can now be directly coupled with 'material properties' in FEM analyses. The coupled FEM–creep damage model was used to successfully simulate the simultaneous

microstructure and stress evolution in typical small tensile test-bar structures.

Applying the integrated GMA creep–FEM code to large structures is still computationally prohibitive. Instead, for the thermo-structural analysis of the DCLL TBM structure a true stress-curve of F82H ferritic steel developed by the GMA creep–FEM model was used. A 5-channel section of the US-ITER DCLL TBM was analyzed. High-temperature ITER Structural Design Criteria [8] to prevent progressive deformation (cyclic creep-ratcheting) were applied. All primary plus secondary stress limits were satisfied.

Because the direct implementation of the GMA creep in a large-scale FEM analysis is still computationally prohibitive, a 'global-to-local zooming' approach is proposed. It is suggested that first a large-scale damage-free FEM analysis be performed to determine the stress state of critical areas, which is then followed by local and detailed fully coupled GMA creep–FEM analysis.

Acknowledgement

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