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Structural analysis of a plasma facing component reinforced with fibrous metal matrix composite laminate

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Abstract

Fiber-reinforced metal matrix composites (FMMC) show improved mechanical performance compared to conventional alloys. Hence, integration of FMMC in plasma facing components (PFC) is expected to improve the structural reliability of the component. A possible design concept for a FMMC-integrated PFC would be such that a cross-ply laminate interlayer consisting of unidirectional FMMC laminae is locally inserted into the highly stressed domain, e.g. bond interface region. To assess the design feasibility of a FMMC-integrated PFC, dual scale stress computation was conducted on a PFC system consisting of tungsten armor/copper-base FMMC laminate interlayer/copper alloy heat sink. Focus was placed on the evolution of stress state, plastic deformation and local damage both on macro- and microscales under heat flux cycling. For this, an incremental micromechanics algorithm was implemented into a finite element code. Results showed that damage in the FMMC would not be critical under fusion-relevant loading condition.

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1. Introduction

The heat flux to be deposited on the surface of plasma facing components (PFC) of a future fusion reactor may reach up to 20 MW/m^2 under quasi-stationary conditions. Since PFC will be subjected to cyclic high heat flux (HHF) loads, high thermal conductivity, sufficient fatigue strength and creep resistance at elevated temperatures are required. Copper alloys have been considered as a structural material for the heat sink substrate of a PFC due to their excellent thermal conductivity [1]. However, insufficient high temperature strength and large thermal expansion are the main limitation from a structure-mechanical viewpoint. Even with metallurgical hardening techniques like precipitation or dispersion, copper alloys have not been able to fully meet the high temperature strength requirement for fusion applications.

Fiber-reinforced metal matrix composites (FMMC) normally show significantly improved mechanical performance in comparison to conventional alloys. This feature becomes more salient in the case of high temperature application due to the excellent high temperature stability of the fibers [2,3]. Hence, it is expected that the structural reliability of PFC will be improved by integration of FMMC. Continuous SiC fibers have been used primarily as a reinforcing element for high temperature structural components like aircraft engine turbines. A candidate design concept for a FMMC-integrated PFC would be such that a cross-ply laminate interlayer consisting of unidirectional FMMC laminae is locally inserted into the highly stressed domain, e.g. the bond interface between plasma facing armor and an actively cooled heat sink.

To assess the design feasibility of a FMMC-integrated PFC, nonlinear dual scale finite element stress analysis was conducted on a model PFC system consisting of tungsten armor/copper-base FMMC laminate/copper alloy heat sink. Tungsten has been considered for a high-Z plasma facing material (PFM) for future fusion devices [4]. In the dual scale analysis technique, the field

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quantities are computed on macro- and microscales simultaneously. Focus was placed on the evolution of stress state, plastic deformation and local damage in individual microscopic phases under thermal cycling. To this end, an incremental micromechanics algorithm was implemented into a finite element code. In this paper, first results of the dual scale structural analysis are presented.

2. Computation model

The whole computational procedure consists of two main steps: (1) finite element analysis (FEA) of component global stress states and (2) micromechanical estimation of local stress states in each constituent phase. Since the matrix behavior was assumed to be thermo-elasto-plastic, an incremental micromechanics model based on the Mori-Tanaka mean field method was implemented into the commercial finite element code ABAQUS in the form of a user-defined subroutine. This subroutine was originally developed by Pettermann et al. [5]. A flow chart of the computational procedure is illustrated in Fig. 1. It is characteristic that additional iterations should be performed in each increment to correct Euler-backward behavior in the macroscopic composite stress caused by the matrix stress updating after plastic yield. To verify this numerical technique a test simulation was done for a titanium based FMMC laminate subjected to thermo-mechanical tensile loading–unloading cycles. It was proved that this approach could reproduce reasonable stress–strain responses showing a good agreement with experimental results for the first load cycle.

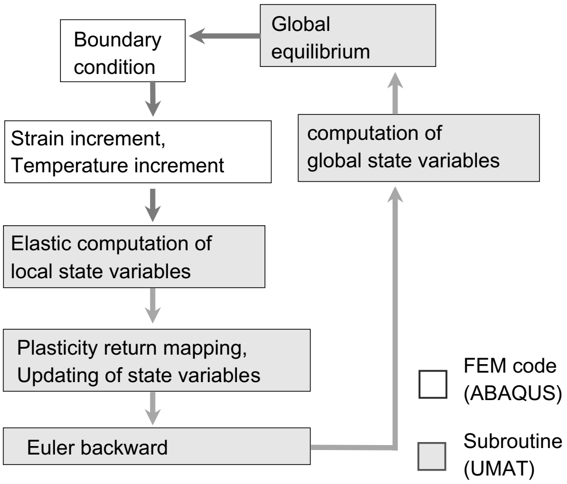

Fig. 1. Structure of the computational procedure for dual scale finite element analysis.

Schematic geometry of the actively cooled model PFC considered for the present analysis is shown in Fig. 2. The corresponding mesh in a typical deformed structure under HHF load is shown in Fig. 3. Only the symmetric half of the PFC was modeled for FEA. Symmetry boundary conditions were applied for planar constraint of the cross-sections. The number of elements and nodes were 2300 and 17 700, respectively. Three-dimensional composite laminate elements were used for the FMMC laminate layer while quadrilateral hexahedral continuum solid elements were used for the other parts. The mesh showed a sufficient solution convergence except the nearest domain of the interface free surface edge.

A coupled thermal–mechanical analysis was carried out in which temperature development during the HHF loading and corresponding thermal stress evolution are computed separately in sequence. A uniform heat flux of 15 MW/m^2 was assumed to be deposited on the surface of the plasma facing armor. Water coolant temperature of 250 °C was supposed. A residual stress field generated by joining process (i.e. cooling from a elevated temperature) was considered. The stress free temperature was assumed to be 700 °C. The selected material properties used for the FEA are listed in Table 1. Temperature dependence of the properties was taken into account. The current micromechanical FEA algorithm showed a stable behavior with change of material parameters. For simplicity, perfect bonding of the fiber/matrix interface was assumed. This simplification might be justified by the loading nature of the assumed cross-ply laminate structure in which the most applied forces were primarily carried by the fibers in the axial directions. Under

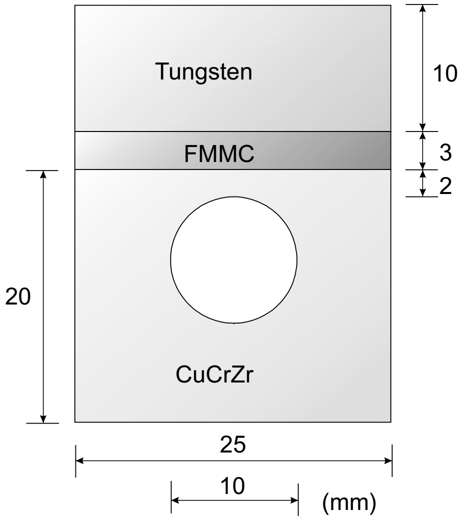

Fig. 2. Geometry of the actively cooled PFC considered for present analysis. The PFC system consists of tungsten armor/copper-base FMMC laminate/copper alloy heat sink.

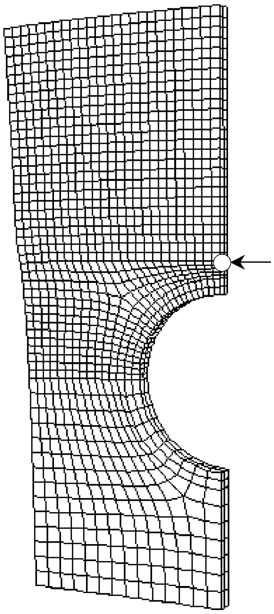

Fig. 3. Three-dimensional finite element mesh used for the dual scale stress analysis.

Table 1
Properties of the matrix and the fiber at room temperature [6]

	CuCrZr	SiC fiber
Young's modulus (GPa)	128	430
Poisson's ratio	0.3	0.17
Yield stress (MPa)	300	
Work hardening rate (MPa)	1050	
Thermal conductivity (W/m °C)	380	16
CTE[a] (10^{-6}/°C)	15.7	5.7

[a] Coefficient of thermal expansion.

this condition interface debonding would not be strongly promoted.

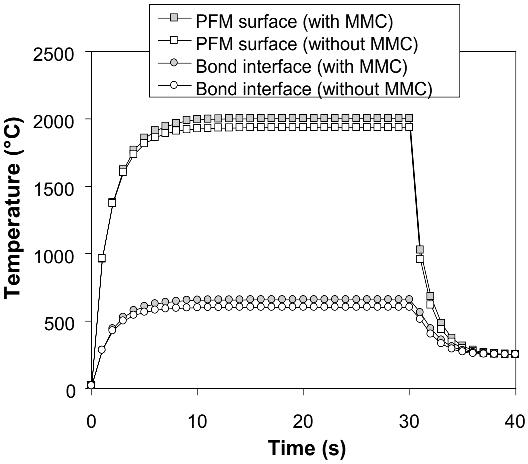

Fig. 4. Development of temperature in the FMMC-PFC and in a conventional PFC without FMMC having the same materials and geometry. High heat flux load of 15 MW/m^2 and coolant temperature of 250 °C were assumed.

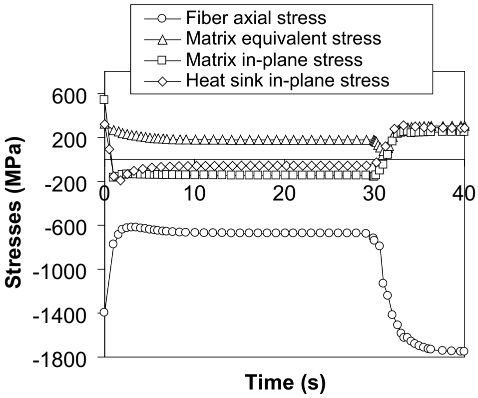

Fig. 5. Stress evolution in the fiber and the matrix of the FMMC laminate at the near-interface position indicated by a circle in Fig. 3.

3. Results and discussion

In Fig. 4 the temperature development at the PFM surface as well as at the bond interface during the HHF load cycle is plotted. For comparison, the corresponding temperature for a conventional W/CuCrZr PFC without FMMC interlayer is also plotted. The temperature difference at steady state is less than 70 °C at both locations. This indicates that the influence of the FMMC interlayer on the rate of heat removal via the PFC is relatively small.

In Fig. 5 the microscale stress evolution in the composite at the near-interface position indicated by a circle with an arrow in Fig. 3 is plotted. In the cold phases (residual stress state or cooling phase) the fiber axial stress is in a compressive state while the matrix stress (in-plane component) is tensile. The thermal stresses in each constituent of the FMMC are significantly relieved when the PFC is heated by the HHF load. The sign of the matrix stress is reversed from tensile to compressive on heating. This is due to the bending of the PFC induced by high temperature gradient under the HHF load. The maximum fiber stress is far from the mean fracture strength of the SiC fiber (SCS6) which amounts 3.8 GPa. The magnitudes of the von Mises matrix stress reveal that considerable plastic flow took place in the matrix. Due to the technical restriction of the algorithm the interfacial stresses could not be obtained. The large fiber

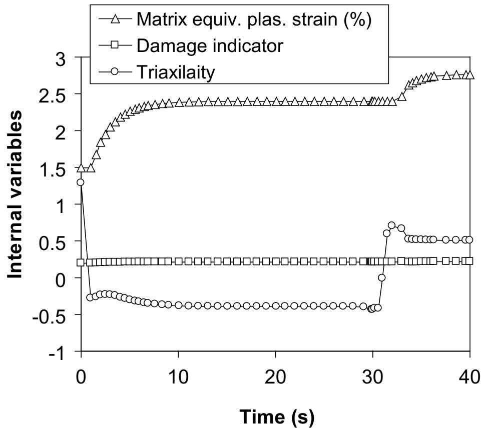

Fig. 6. Evolution of ductile damage indicator, stress triaxiality in the matrix and equivalent plastic strain during the HHF cycle.

normal stresses suggest that the interfacial stresses would be correspondingly high. Hence, it is reasonable to infer that the sliding mode debonding at the fiber interfaces may occur. If a local debonding at the fiber/matrix interface once takes place, this will cause an abrupt increase of the fiber stress due to the extinction of the load transfer at the site. However, even in the case of tensile loading, such situation will not be critical since the fibers are under strong compression and the additional tension will just decrease the magnitude of the compressive fiber stress. This issue is not treated in detail here because it requires an extended further study.

In Fig. 6 the evolution of several internal variables are plotted. The ductile damage indicator stands for a measure of damage level in the matrix [5]. It is an exponential function of normalized stress triaxiality being integrated over equivalent plastic strain and scales from zero to unity which corresponds the undamaged state and the onset of a microcrack, respectively. The result shows that the ductile damage indicator remains nearly constant. It remained limited below the 0.2 which was developed by residual stress, although the accumulated equivalent plastic strain stepwise increases during the load cycle. This behavior is attributed to the compressive hydrostatic stress state in the matrix which suppresses the growth and coalescence of microvoids. This condition might be interpreted as a positive aspect of the FMMC-PFC concept, that is, the stress concentration zone of a bi-material PFC can be strengthened by insertion of a FMMC-interlayer without 'serious' microscopic failure developing in the composite laminate under HHF load.

4. Conclusion

For the design feasibility study of a FMMC-integrated PFC, a micromechanics-based dual scale stress analysis was conducted on a model PFC system consisting of tungsten armor/copper-base FMMC laminate/copper alloy heat sink. The evolution of stress state, plastic deformation and local damage on microscale under thermal cycling was investigated assuming a perfect fiber/matrix interface. The results showed that the fiber normal stress was compressive and remained in a safe state. The plastic deformation of the matrix induced ductile damage which was restricted to a sufficiently low level during the whole load cycle. This behavior is attributed to the compressive hydrostatic stress state in the matrix which suppresses the growth and coalescence of microvoids. It is expected that the possible debonding process at the fiber/matrix interface will not cause a serious consequence in composite failure. This condition is promising for the development of the FMMC-PFC concept.

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