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Numerical design optimization of plasma-facing components using functionally graded materials

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Divertor plasma-facing components (PFCs) of future fusion devices will have to deal with even more extreme heat loads than encountered at present. For ITER, it is expected that the current monoblock concept, where tungsten blocks are mounted on a copper cooling duct, will be sufficient. However, it is unsure whether these monoblocks can withstand the even more extreme conditions expected in future machines such as DEMO [1]. Therefore, solutions are required that either reduce the heat load or that improve the PFC design. Concerning the latter, several novel material concepts have arisen over the past decades, such as functionally graded materials (FGMs). These FGMs allow tailoring the local material properties in order to mitigate stress concentrations and therefore increasing the lifetime of the PFCs [2]. However, designing these components optimally in a manual way becomes cumbersome considering the large amount of degrees of freedom in the design, especially when additional design constraints have to be satisfied. For example, tungsten recrystallization and embrittlement has to be prevented by keeping the local temperature between the ductile-to-brittle transition temperature (DBTT) and the recrystallization temperature during operation wherever tungsten is present.

In this contribution, which is based on [3], we show how gradient-based numerical optimization methods can be used to quickly and automatically find the best possible design. A key ingredient here is the adjoint approach that allows all sensitivities to be computed with only a single additional simulation step, regardless of the amount of design variables. We apply this methodology to find the optimal material distribution in a W-Cu FGM-based ITER-like monoblock that minimizes the stress concentrations under steady loading conditions. At the same time, constraints on the local temperature are included to automatically prevent tungsten recrystallization and embrittlement for the operational scenario envisaged. To this end, a novel augmented Lagrangian strategy was employed to deal with arbitrary engineering constraints. We show that the optimized designs lead to significant stress reductions in the bulk of the monoblock, though the obtained design depends on model uncertainties, such as the stress-free temperature, and on the cost function formulation and constraints considered. For the latter, especially the DBTT of tungsten was shown to have a profound influence on the final design. In the future, characterization of and design for unsteady heat loads should be considered as well, given the importance of thermal cycling and fatigue due to for example fast transients and the pulsed operational regime.

Finally, we present an outlook on how the methodology can be applied for other design concepts, for example the design of first wall components, additively manufactured composites, different coolant channel geometries, shaping of the plasma-facing surface of the monoblocks, ⋯Given that these techniques allow to quickly explore the potential of these novel designs in a cheap way, the design process can be significantly accelerated.

[1] J. H. You et al., Nucl. Mater. Energy 9, 171-176 (2016)
[2] J. W. Coenen et al., Phys. Scr. T167, 014002 (2016)
[3] S. Van den Kerkhof et al., Nucl. Fus. 61, 046050 (2021)

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