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Enhancing the DEMO divertor target by interlayer engineering

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HIGHLIGHTS

- The European 'near-term' DEMO forsees a water-cooled divertor.
- Divertor targets typically use an interlayer between the armour and structure.
- Engineering the properties of the interlayer can yield large gains in performance.
- A response surface based design search and optimisation method is used.
- A new design passes linear-elastic code rules up to applied heat flux of 18 MW/m^2.

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ABSTRACT

A robust water-cooled divertor target plate solution for DEMO has to date remained elusive. Common to all contemporary concepts is an interlayer at the boundary between the tungsten armour and the cooling structure. In this paper we show by design optimisation that an effectively designed interlayer can produce dramatic gains in power handling. By engineering the interlayer as part of the design study, it is found that divertor performance is enhanced by either a low conductivity 'Thermal Break' interlayer or an 'Ultra-Compliant' interlayer. For a 10 MW/m^2 surface heat flux we find that a thermal conductivity of 15 W/mK and elastic modulus of 1 GPa are effective. A design is proposed which passes linear-elastic code rules up to an applied heat flux of 18 MW/m^2.

1. Introduction

The engineering of the divertor target remains a major challenge in the design of DEMO (a demonstration fusion power reactor). The target structure must survive an environment of extremely high heat fluxes (tens of MW/m^2), intense neutron irradiation and aggressive surface sputtering, while also satisfying plant low activation criteria. The European fusion Roadmap foresees a 'near-term' DEMO, a long-pulsed device with technology based on realistic extrapolation from ITER [1]. In this device low-temperature water is used as the baseline divertor coolant as it can achieve much higher heat transfer rates than a gas-cooled system.

Contemporary water-cooled target concepts are based on the ITER design, and comprise a CuCrZr structural pipe surrounded by a tungsten monoblock as the plasma facing material (Fig. 1) [2]. CuCrZr suffers embrittlement under irradiation and has a narrow operating temperature window but is thought to be an acceptable material in the low neutron fluence divertor region. Tungsten is considered the most suitable armour material due to its refractory nature, good conductivity and low sputter yield. Between these two materials is an interlayer, which in ITER is pure copper. This interlayer facilitates joining of the parts and is often regarded as a compliance layer. Although it is not seen as a structural component, the interlayer is pivotal to the structural performance of the target. In this paper the 'Thermal Break' concept is proposed and it is shown by design search and optimisation that an effectively engineered interlayer can yield dramatic gains in power handling.

2. A divertor target with a "Thermal Break"

In a divertor target element as shown in Fig. 1, there are three sources of stress in the structural (pipe) material: (1) the internal pressure of the water coolant; (2) the temperature gradient due to the applied heat flux; (3) the difference in thermal expansion

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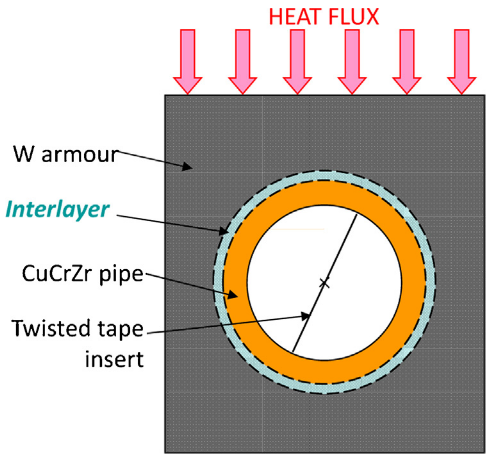

Fig. 1. Generic water-cooled divertor target concept.

between the CuCrZr pipe and the tungsten armour. Under typical operating conditions, the third source of stress, i.e., mismatch in thermal expansion, can dominate the overall stress field. It is therefore vitally important that this component of stress is reduced.

If one makes the assumptions of two concentric thin-walled pipes, uniform heat flux on the outer circumference and plane stress, the mismatch stress between the two pipes σ_{mismatch} can be expressed as

$$\sigma_{\text{mismatch}} = \frac{\alpha_2(T_{2,\text{average}} - T_0) - \alpha_1(T_{1,\text{average}} - T_0)}{(1-\nu_2)t_1/t_2E_2 + (1-\nu_1)/E_1} \quad (1)$$

where α is the coefficient of thermal expansion, t is wall thickness, T is temperature (average across t, or reference $T_0 = 22\,^\circ\text{C}$), ν is Poisson's ratio, E is Young's modulus and subscripts 1 and 2 denote the inner and outer pipes, respectively. This model illustrates two points. First, if subscript 1 denotes the CuCrZr pipe and 2 denotes the interlayer, the mismatch stress is reduced if the interlayer thickness and elastic modulus (t_2 and E_2) are reduced. This increased compliance is widely adopted and in ITER-like designs is embodied by a thin layer of pure copper.

Second, if 1 denotes CuCrZr and 2 denotes tungsten, then because α_2 ($4\,\mu\varepsilon/^\circ\text{C}$ at $150\,^\circ\text{C}$) is much lower than α_1 ($17\,\mu\varepsilon/^\circ\text{C}$), the compressive mismatch stress is reduced by increasing the tungsten temperature T_2 while reducing (or limiting) the CuCrZr temperature T_1. This step in temperature or 'Thermal Break' between the two materials can be realised by using an interlayer with a low thermal conductivity. The Thermal Break is illustrated graphically in Fig. 2.

The Thermal Break concept is quite unintuitive, since it reduces overall conductance of heat. However, the idea of an interlayer with limited conductance is not new; Li-Puma et al. [2] have in the past proposed a carbide "thermal barrier" interlayer, although the purpose of this was as a "heat flux repartition" layer rather than a direct means of reducing stress in the structure.

The potential benefits of engineering the properties of the interlayer in this way are: (1) reduced structural stress brought about by a large temperature rise between the CuCrZr and tungsten; (2) reduced stress if the interlayer is also very compliant; (3) more favourable material properties if the Thermal Break is designed such that the CuCrZr and tungsten are operating close to their recommended temperature windows; (4) reduced peak heat flux upon the coolant channel (pipe) as a result of power flowing deeper around the W monoblock, giving a greater margin to critical heat flux (CHF).

In this design study, we vary the interlayer stiffness, thermal expansion coefficient and thermal conductivity as well as geometric variables in an automated design search and optimisation process, in which the primary objective is maximising the margin to structural failure in the CuCrZr pipe.

3. Design optimisation procedure

Below is an overview of the computational design search procedure used in this work; for more detail the reader is referred to a report by Barrett et al. [3].

3.1. Finite Element model

The optimisation of designs requires an analysis method to calculate a metric of performance. The divertor target is analysed using a thermo-structural finite element sub-model (Fig. 3) of one-half a monoblock with symmetry on the cut (y-z) plane. Half an inter-monoblock gap is modelled, giving a stub of pipe on the end of which the nodes have a coupled displacement constraint in the x (axial) direction. The underside mid-plane corners of the monoblock are constrained in the vertical (y) direction with one corner fixed in z and the other sliding. The thermal solver takes an applied surface heat flux ($10\,\text{MW/m}^2$ in all design studies), coolant temperature and uses spatially varying wall heat transfer coefficient (CEA and Tong75 [4,5]) to calculate a temperature field for input to the structural solver which calculates the stress and strain

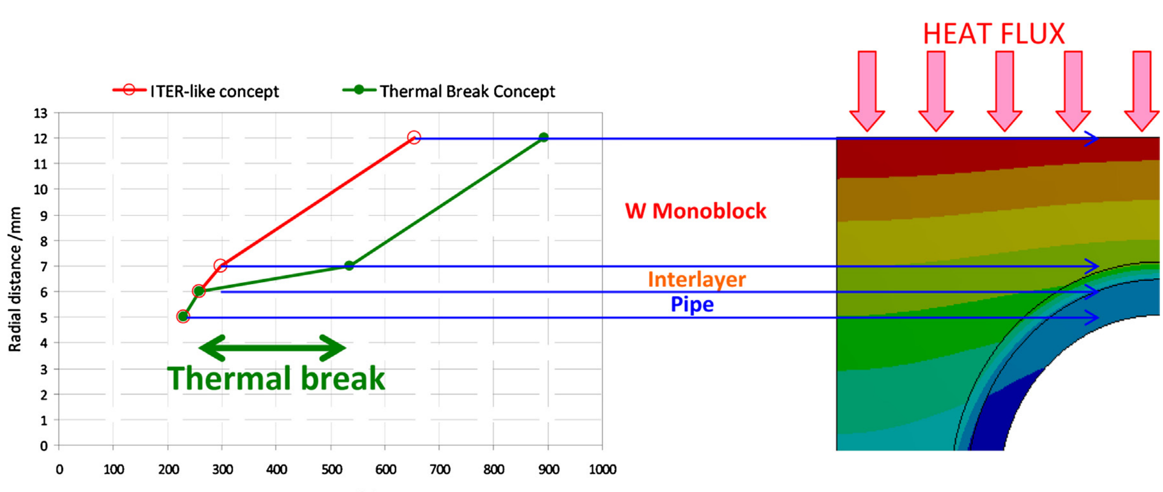

Fig. 2. Illustration of the Thermal Break concept: temperature vs. radial distance vertically through the divertor target.

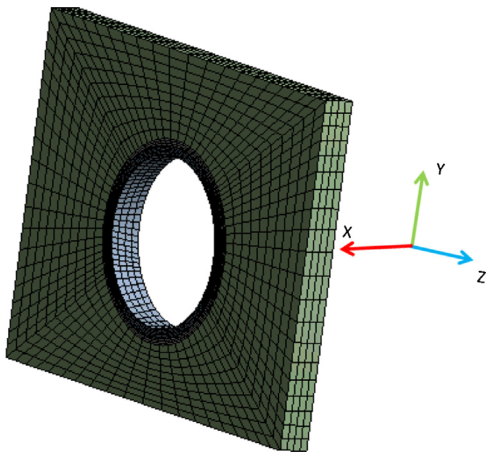

Fig. 3. Finite element model used in the design studies.

field. In all analyses the structural/pipe material is CuCrZr-IG, the monoblock is tungsten, and the interlayer is pure copper with E, α and k set as variables of the design process. All materials are in perfect bonded contact with properties (un-irradiated and irradiated) taken from the ITER SDC-IC and Material Properties Handbook [6,7].

3.2. Objective function calculation

The ITER SDC-IC [6] linear elastic design criteria are used to calculate a design metric which the optimiser uses in the search for better designs. In each call of the analysis model (Section 3.1), nine radial paths are defined spanning the pipe wall which are spaced equally around 180° from top to bottom. Linearised stresses are calculated on each path, which are compared to stress allowables (a function of path temperature) to calculate a reserve (safety) factor for each failure mode assessed. The lowest reserve factor of all failure modes and of all nine paths in each analysis is termed the minimum reserve factor and this quantity is maximised by the optimiser. This method helps to ensure that unanticipated failure modes are accounted for in the optimisation.

This "design by analysis" approach to the structural material failure assessment does not account for the effects of manufacturing processes such as residual stress or deterioration of mechanical properties, and we do not attempt to assess the integrity of the W-Cu-CuCrZr joint. Indeed, the ITER SDC-IC applies the "design by experiments" approach for such joints. However, the analysis used here is intended for design space exploration; when it comes to absolute failure assessment then the effect of manufacturing processes must be considered.

3.3. Optimisation methodology

The optimisation strategy employed is the method of response surfaces. The design space is initially seeded with an efficient spread of design points using design of experiments. A surface is then fitted to these points, which is used as a surrogate of the true objective function, allowing a thorough search of the design space using a global optimiser. The surface model used is Kriging due to its ability to assess confidence in the response surface and expected improvement in areas away from design points. Typically we refine the response surface using new design points until the level of predicted relative error is below 5%. A multi-objective genetic algorithm is used to search the response surface. The primary objective is the maximisation of the minimum reserve factor (Section 3.2) with additional temperature constraints being the CuCrZr limit of

Table 1
Design optimisation variables and final design values.

Parameter	Lower bound	Upper bound	Design
Surface heat flux [MW/m^2]			10
Coolant velocity [ms^{-1}]	–	–	20
Coolant bulk pressure [MPa]	–	–	5
Coolant bulk temperature [°C]	–	–	200
Interlayer thickness [mm]	0.25	0.5	0.5
Interlayer copper fraction	0.01	0.3	0.03
Tungsten side thickness [mm]	3	7.5	4.04
Tungsten depth [mm]	2	6	3.66
Pipe thickness [mm]	0.5	1	0.52
Pipe inside diameter [mm]	–	–	10
Tungsten top thickness [mm]	–	–	5
Tungsten bottom thickness [mm]	–	–	3.5

350 °C [1] and an assumed temperature limit of tungsten (to avoid re-crystallisation) of 1300 °C.

4. Design optimisation results

The design studies involved a number of response surfaces of varying size and dimensionality with the results of each study informing the next. For brevity only the final optimisation study is reported here.

The design study variables and their bounds as well as fixed parameters are listed in Table 1. In the first instance the interlayer properties (E, α and k) are controlled using a single design variable, termed 'interlayer copper fraction', which is a linear scale factor of the properties for copper. Certain parameters such as pipe diameter, tungsten 'top' thickness (above the pipe) and coolant parameters are fixed at practicable values as we find the optimiser always chooses them to be on the bounds of the design space.

The 'optimal' design parameters resulting from the design optimisation are listed in Table 1. The chosen design has a thick interlayer with a very low interlayer copper fraction, i.e., poorly conducting and compliant. The response surface shows little sensitivity to tungsten monoblock (axial) depth but a strong correlation between monoblock width and pipe diameter. Fig. 4 displays contours of Von Mises stress in the new design. The maximum stress in the pipe is 135 MPa, occurring at the bottom of the pipe. It can be

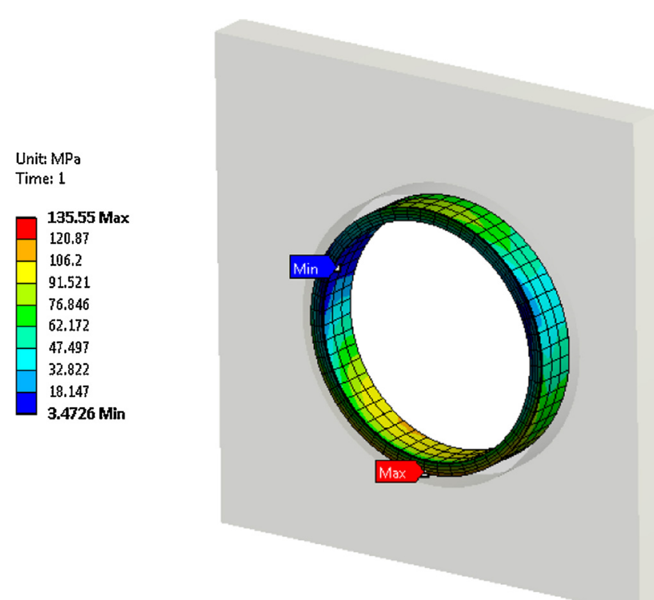

Fig. 4. Equivalent (Von Mises) stress contours in an 'optimised' Thermal Break divertor target.

Table 2
Summary of ITER SDC-IC design assessment.

Failure mode and rule	T (°C)	Analysis criterion	Reserve factor
IC 3211.1 "Immediate Plastic Collapse and Plastic Instability" $P_m < S_m$	212[a]	108 MPa	>5
IC 3211.1 "Immediate Plastic Collapse and Plastic Instability" $P_m + P_b < K_{eff}S_m$	212[a]	161 MPa	>5
IC 3212.1 "Immediate Plastic Flow Localisation" $P_L + Q_L < S_e$	208	125 MPa	1.4
IC 3213.1 "Immediate Local Fracture due to Exhaustion of ductility" $P_L + P_b + Q < S_d$	210	262 MPa	2.16
IC 3214.1 "Global Fast Fracture" $K_{I,global} < 0.33\, K_{IC}$	210	33 MPa m$^{-1/2}$	>5
IC 3214.2 "Local Fast Fracture" $K_{I,local} < 0.67\, K_{IC}$	210	66 MPa m$^{-1/2}$	>5
IC 3311.1 "Progressive Deformation or Ratcheting" (3 Sm) $P_L + P_b + Q + F < 3\, S_m$[b]	209	326 MPa	2.7
IC 3320 "Time Independent Fatigue" Allowable Cycles	209	Predicted cycles to failure >10^5	

[a] Analysis at 22 °C, criterion evaluated at local operating temperature of 212 °C.
[b] ITER SDC-IC rule IC3311.1 does not strictly include the peak stress, F. However, we include this quantity as a pragmatic means of realising the intent of the rule, in a way which is also "conservative" for this analysis case.

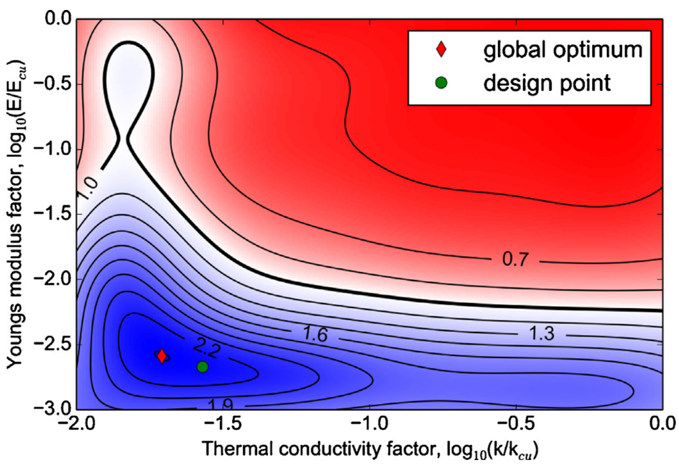

Fig. 5. Response surface showing contours of minimum reserve factor as a function of the interlayer Young's modulus and thermal conductivity.

seen that the optimiser has quite effectively distributed the stress around the pipe in an attempt to reduce the peak value.

Table 2 gives a summary of the assessment of the design against the ITER SDC-IC rules. At the design heat flux of 10 MW/m^2, all criteria are passed and the minimum reserve factor is 1.4. The peak wall heat flux at the top of the pipe is 12.3 MW/m^2 with a margin to CHF of 2.2. Critically, the maximum tungsten temperature is 1298 °C, i.e., on the limit of the imposed constraint. However, if we ignore this constraint on tungsten temperature and consider only the CuCrZr structural integrity, by ramping the applied heat flux we find the first structural failure at 18 MW/m^2 (by plastic flow localisation). This very promising result invites further study into the importance of the Thermal Break effect.

5. Exploring interlayer parameter sensitivity

Next, instead of controlling the interlayer properties as a single parameter, the optimisation has been run with the interlayer E, α and k separately parameterised. Each is expressed as a fraction of the values for copper, with bounds $0.001 < E/E_{cu} < 1$, $0.1 < \alpha/\alpha_{cu} < 1$, $0.01 < k/k_{cu} < 1$. With knowledge of the response surface, the spacing of E and k points in the initial seed is on a log scale. As before, all designs are analysed for 10 MW/m^2 surface heat flux.

By treating the three interlayer variables independently, the optimiser finds a large volume of the design space where minimum structural reserve factors above 2 are found. The resulting response surfaces reveal that the designs are broadly insensitive to α, but strongly dependent on E and k. Fig. 5 shows the response surface for varying E and k with all other variables fixed at their optimal values. This response surface features two distinct plateaus. If $E/E_{cu} > 0.01$, i.e., the interlayer E is greater than roughly 1 GPa, the occurrence of the Thermal Break effect means that designs are very dependent on interlayer k and only designs with $k/k_{cu} < 0.03$ ($k < 15$ W/mK) can achieve a minimum reserve factor above unity. However, at very low $E/E_{cu} < 0.01$ the Thermal Break is relatively ineffective, as the interlayer structurally decouples the monoblock and CuCrZr, and the structure effectively only experiences the thermal gradient stress. Using such an 'Ultra-Compliant' interlayer, minimum reserve factors above 1.6 can be achieved with conductivity approaching that of copper. Such designs would have the advantage of keeping the tungsten cooler. Indeed, in this region of the surface a design was identified which passes all the SDC-IC rules and satisfies the 1300 °C tungsten temperature limit, up to a maximum surface heat flux of 16.5 MW/m^2.

6. Implementing an engineered interlayer

In this work it is shown that engineering the properties of the interlayer can greatly enhance divertor power handling. Clearly, an important next step is to try to realise our ideal interlayer parameters in a practical divertor target design. A low conductivity interlayer is likely to be straightforward to implement and this alone would yield promising gains. However, the pursuit of a material with Ultra-Compliance which is suitable for the DEMO environment is more challenging. A true structural decoupling could be achieved with a liquid-metal interlayer, but this would require substantial R&D. The Authors are experimenting with practical Thermal Break materials as detailed in a companion paper [8].

7. Conclusion

The potential for enhancing water-cooled divertor target power handling by engineering the interlayer has been demonstrated by use of a design search and optimisation procedure. The principal of a Thermal Break interlayer has been introduced, which can dramatically improve structural performance by reducing the thermal mismatch stress at the armour interface and increasing the margin to CHF. A design has been found which passes the ITER SDC-IC linear elastic design rules up to an applied heat flux of 18 MW/m^2.

Further, if a practical design could be devised, perhaps more important is an Ultra-Compliant interlayer which structurally decouples the tungsten armour and CuCrZr cooling structure. The response surface models presented here suggest that the interlayer elastic modulus should be less than 1 GPa. This alone effectively eliminates the thermal mismatch stress and lessens the need for a Thermal Break. This may be essential if a maximum tungsten temperature limit is design driving.

Further design studies and experiments are underway to develop practical materials to realise this potential.

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