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Conceptual design study for CFETR divertor target using CLAM steel as structural material

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ABSTRACT

Monoblock technology with CuCrZr as the structural material is the standard divertor target design for the initial phase of the China Fusion Engineering Test Reactor (CFETR). The design concept with China Low Activation Martensitic (CLAM) steel as the structural material provides another candidate solution for the CFETR divertor target.

This paper presents a design study of an optimized monoblock to meet the requirements for CFETR operating conditions, which establishes a good basis for engineering design of CFETR. The monoblock uses tungsten as armour and CLAM steel as the structural material, with a copper interlayer. The operating temperature window of CLAM steel was determined by irradiation embrittlement, softening, and other aging effects. Initial design rules for the W/CLAM monoblock were checked; thermal results by finite element analysis (FEA) show that the design concept is able to withstand a heat flux of 10 MW/m^2 after examining the temperature for each material and the margin to the wall critical heat flux (WCHF) on the tube. Mechanical results indicate that the CLAM steel meets the ITER SDC-IC elastic rules under potential irradiation level of CFETR, irrespective of residual stress. Also the fatigue criteria were checked for unirradiated conditions with a reasonable life time of 16,000 cycles.

1. Introduction

China Fusion Engineering Test Reactor (CFETR), a necessary step between ITER and DEMO (demonstration reactor), aims at demonstrating a tritium, self-sustained Tokamak device with fusion power of 50–200 MW and duty cycle of 0.3–0.5 [1]. Conceptual design of CFETR has been carried out since 2013 [1,2].

The engineering conceptual design of CFETR divertor was presented in Ref. [3] with preliminary divertor geometry, cooling system and remote maintenance for three plasma configurations (snowflake, ITER-like and super X). For the divertor plasma facing unit (PFU) structure, an ITER-like, water-cooled, monoblock technology (tungsten for armour, CuCrZr for heat sink and Cu forinterlayer between them) was proposed for the first operation phase of the CFETR [1,3]. Thermo-hydraulic analysis for this type of divertor by Chen et al. [4], which focused on the structural behavior at different mass flow rates, provided preliminary validation of the design feasibility of the CFETR divertor for the initial phase.

However, the expected maximum irradiation doses of the CFETR first wall in phase-Iand phase-II are 10 dpa and 50 dpa, respectively, according tothe development road map of CFETR [7]. Irradiation is known to produce lattice defects in materials leading to embrittlement and reduced thermal conductivity [8]. China Low Activation Martensitic (CLAM), one of the reduced activation ferritic/martensitic (RAFM) steels, has been developed for years in China. CLAM is a candidate structural material for the CFETR [1] divertor PFU for its good thermal conductivity, low thermal expansion coefficient, good resistance to radiation-induced swelling and helium embrittlement et al. [5]. Meanwhile, R&D activities on joining techniques and fabrication [9], like hot isostatic pressing (HIP) welding and HIP diffusion bonding,-provide feasibility for the W/CLAM divertor PFU. Mao et al. [6] carried out a thermo-mechanical analysis on the divertor PFU with CLAM steel as structure material and an optimized geometrical monoblock has been obtained which provides a preliminary design for divertor PFU with CLAM steel.

For further CFETR design, thermal-mechanical analysis of the divertor PFU under irradiation is essential. This paper presents a thermal-mechanical analysis of a geometrically-optimized, water cooled divertor PFU using CLAM steel as the structural material for CFETR. The analysis results were assessed against the thermal and mechanical rules.

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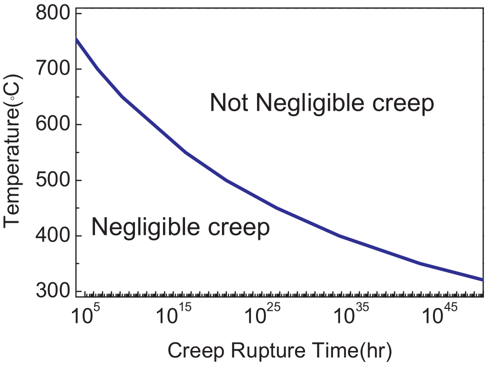

Fig. 1. Negligible thermal creep time limits for CLAM steel.

2. Assessment rules

Combined rules from the Structural Design Criteria for ITER in-vessel components(SDC-IC) and Monoblock Elastic Analysis Procedure (MEAP) for EU Demo divertor are employed for assessing the W/CLAM monoblock.

Thermal rules are taken directly from MEAP: (1) The maximum heat flux at the coolant pipe wall is assessed against the critical wall heat flux (WCHF) as defined by the CEA modified TONG75 correlation [10]; (2) Tungsten temperatures are assessed against a suggested 1300 °C maximum. Assuming a roughly linear thermal gradient to the pipe temperature, this equates approximately to two thirds of the tungsten remaining below there crystallization temperature [11]; (3) The allowable CLAM steel pipe temperatures are set by a lower bound to avoid loss of ductility caused by irradiation, and an upper bound to avoid excessive creep or irradiation softening like CuCrZr, and the temperature range is summarized in the next section.

Structural rules from SDC-IC are adopted. First, creep properties of CLAM steel are tested [12] and a Larson-Miller formula is derived to show the relationship between creep temperature and rupture time, as shown in Fig. 1. Then the negligible thermal creep test (IC 3050) criteria are satisfied according to Eq. (1). The total operating period is divided into N intervals of time. For each interval i, of a duration t_i, the maximum temperature reached is noted T_i,

$$\sum_{i=1}^{N}\left(\frac{t_i}{t_{Ci}}\right)\leq 1 \tag{1}$$

where t_ci is the allowable time at temperature T_i, given in Fig. 1.

The applicable design rules are referred to as “low-temperature rules” [13], for which the M-type (IC3121) is employed here. Note that the procedure is used for an initial design assessment only, pending the development of the elasto-plastic assessment procedure for W/CLAM steel divertor monoblock designs. Therefore, the fast fracture analysis in M-type damage is not included.

Moreover, the desired elastic modeling of the structural pipe component in CLAM steel can only be used to determine cyclic stress range (but not absolute stress) due to the residual stress. Thus, C-type (IC3130) damage without progressive deformation or ratcheting in SDC-IC (i.e. the 3Sm rule) is applied. This is because this rule remains valid irrespective of the residual stress expected in typical monoblock designs [11].

With regards to residual stress, there is no accurate test measurement after manufacture at this time. But for W/CuCrZr, elastic structural design rules are found to remain valid irrespective of the considerable residual stress expected from monoblock manufacture [14]. Also, the gap between the coefficients of thermal expansion (CTE) of CLAM steel and tungsten [15] is less than that between tungsten and CuCrZr [16] which probably means the residual stress in the CLAM tube after HIP is less than in the CuCrZr tube. In conclusion, the 3Sm rule seems suitable for the initial design assessment.

3. Operation temperature of CLAM steel

It is reasonable that the heat sink material is subjected to a temperature range to avoid critical embrittlement [14]. The ductile–brittle transition temperature (DBTT) of CLAM steel is low [17], but when irradiated, it would be shifted up, like other RAFM steels (e.g. Eurofer). The lower operating temperature limit for CLAM steel due to the embrittlement is recommended as 300 °C [5]. When irradiated at high temperatures between 314 °C and 440 °C, CLAM steel exhibits recovery of work hardening and uniform elongation [18]. So when uniform elongation is used as a criterion, the 314 °C may be regarded as the lower limit of operation temperature for the CLAM steel.

The upper limit of temperature is determined by long-term strength loss due to thermal softening and irradiation creep, etc., but also by a reduction in static mechanical properties [5].

According to the duty cycle [2] and availability analysis [18] of CFETR, the divertor should be able to withstand long pulses for at least 1460 h before failure or replacement. Hence, thermal softening would be a criterion for the CLAM steel upper temperature limit. Shown in some experiments for CLAM steel, softening occurred above 550 °C [19], and that significant softening occurred after ageing at 700 °C for 100 h [20]. In irradiation experiments on CLAM [21], the size of the vacancy cluster is increased primarily with irradiation temperature from RT to 600 °C, and a peak of the void size was observed at about 500 °C under 15 dpa, implying that the swelling is negligible. And at higher irradiation temperatures defect annealing occurs.

From the above, the upper limit of the temperature range for CLAM is recommended as 550 °C.

It is noted that the mechanical properties of CLAM steel, like Young's modulus, density and Poisson's ratio, have a negligible variation with temperature from room temperature (RT) up to 600 °C [22]. Tensile properties such as yield stress and ultimate tensile strength would be decreased byabout 20% when temperature varies from RT to 450 °C [12] which has notable effects on fatigue life. However, irradiation hardening balances the tensile strength loss by temperature rise for irradiated steel at 6.6 dpa [12], which is within the CFETR irradiation dose level.

4. Basis of the conceptual design

4.1. Geometry

As mentioned above, at the preliminary operation phase of the CFETR, the ITER-like monoblock structure is used for the divertor PPU and its capability of heat exhaust is set to stationary 10 MW/m^2 [3]. Hence, the ITER monoblock structure is applied to the present CFETR divertor PFU design, as shown in Fig. 2, with tungsten, OFHC copper, CLAM steel for armor, inner layer and heat sink material, respectively, and a swirl tape(thickness:0.8 mm, twist ratio:2, which is not shown in the figure) in the tube.

A thermal analysis of the W/CLAM monoblock PFU with ITER design geometry was conducted, but the results show that the allowable heat flux is less than 4MW/m^2 which is far from the expected target heat flux of 10 MW/m^2 [6]. Then the principal dimensions such as monoblock depth, thickness, width and diameter, and thickness of the inner tube were optimized. The results, shown in Fig. 2, are obtained as a preliminary design to meet the requirement, which is applied for thermal-mechanical analysis here.

4.2. Hydraulic parameters

As a first study for the W/CLAM case,the inlet water temperature has been set to 314 °C according to the operating temperature of CLAM steel in Section 2. Due to the similar temperature limit for Eurofer of 325 °C [23], the rest of the hydraulic parameters are set similar to those of a Eurofer design: water velocity of 20 m/s and pressure of 15 MPa for