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Creep-Fatigue Damage in OFHC Coolant Tubes for Plasma Facing Components*

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Carbon-carbon (C-C) tiles brazed to water cooled copper tubes provide a concept for heat removal in high flux regions of fusion devices such as ITER. A nearly flawless braze between the C-C and coolant tube can be achieved by the hot isostatic pressing (HIP) process in which high pressure is applied to the surfaces of the components during brazing. The use of annealed oxygen free copper (OFHC) is often considered because its low yield strength not only allows the tube to conform to the C-C interfaces, but also minimizes residual stresses in the C-C that are developed during the brazing process. However, the low creep and fatigue strengths of OFHC cause concern regarding the survivability of the tube through the various operational loading cycles. An elastic-plastic-creep-fatigue analysis was performed for the macroblock design using a simplified axisymmetric structural model. The results show that the strain range induced by 350°C bake cycles exceeds the fatigue criteria after only 160 cycles. Although the creep stress level in the coolant tube is much lower than that for which data is available, use of extrapolated data estimates that high creep damage will occur. Recent high heat flux tests performed by JAERI on C-C saddleblock tile specimens resulted in a water leak due to thermal fatigue stress at the location predicted by the presented creep-fatigue analysis. It is concluded that relatively simple structural models can be used to predict failure in the coolant tubes for high heat flux components. In addition, these results indicate that a copper alloy with greater creep-fatigue properties than OFHC, but still acceptable for the HIP brazing process, is required for the monoblock and similar concepts.

1. INTRODUCTION

The steady-state operation of fusion experiments requires that the plasma facing components (PFCs) be actively cooled. Carbon-carbon (C-C) tiles bonded to water cooled tubes provide the presently preferred concept for heat removal in the high heat flux regions of ITER. The bonded interface for this tile concept is usually accomplished by a brazing process which produces significant residual stresses in the C-C tile and coolant tube. The divertor design favored for the now canceled TPX machine was the macroblock concept. The design utilized a 3-D random weave C-C material bonded to OFHC tubes by a HIP brazing process. In addition to having the capability of maintaining a maximum surface temperature of 1000°C for a steady-state heat flux of 7.5 MW/m², the macroblock design provides a robust structure for reacting halo current loads to a divertor support structure. There is concern that the low creep and fatigue strengths of OFHC will cause a coolant leak failure to occur. Therefore, a relatively simple structural model was developed to estimate the creep fatigue damage in the coolant tubes for the TPX macroblock concept.

2. STRUCTURAL MODEL AND METHODS

The elastic-plastic-creep fatigue analysis of a single coolant tube of the macroblock design was performed using the simplified structural model shown in Fig. 1. The analysis was performed with the ANSYS code [1] using eight node axisymmetric elements. This assumption is reasonable in view of the temperature distribution and the large thickness of the C-C block compared with that of the OFHC tube. Generalized plane strain conditions were imposed on the finite elements in the axial direction of the coolant tube.

The temperature dependent elastic-plastic material properties for annealed OFHC presented in Ref. 2 were used for the analysis. The stress-strain curves for OFHC are assumed to be adequately specified by a bilinear relationship. The C-C material was assumed to remain elastic at all times and its creep rate to be negligible.

The steady-state (secondary) creep strain increment $\Delta\epsilon_{cr}$ as a function of time is computed in the ANSYS code by the following equation:

$$\Delta\epsilon_{cr} = \dot{\epsilon} \Delta t$$

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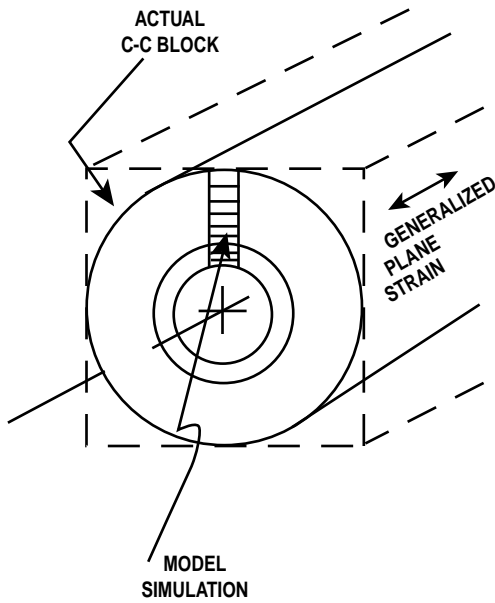


Fig. 1. Plane strain axisymmetric structural model of macroblock.

where Δt = time increment and the secondary creep strain rate is:

$$\dot{\epsilon} = A\sigma^B e^{-C/T}$$

and σ = equivalent stress (Von Mises)
 T = absolute temperature
 e = natural log base

The material creep constants (in SI units) over the temperature range of 260° to 455°C presented in Ref. 3 are:

$$A = 5.91 \times 10^{-4}$$

$$B = 3.429$$

$$C = 7270$$

The load cycles for the TPX macroblock assumed for the analysis are shown schematically in Fig. 2. These cycles represent the cooldown from brazing followed by a bakeout and two operating cycles. A final bakeout cycle is then applied to check that residual stresses are not significantly affected by creep relaxation.

3. ANALYTICAL METHODS AND CRITERIA

The fatigue strain ranges over the assumed loading cycles were extracted from the ANSYS

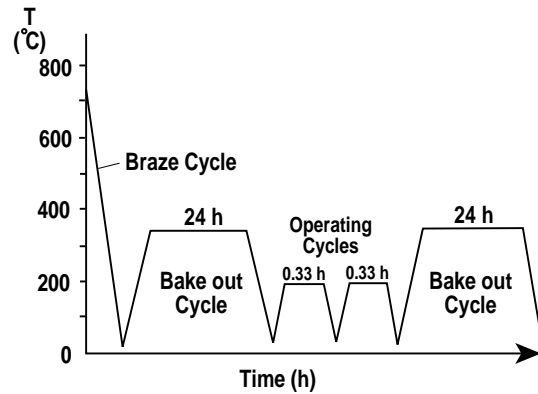


Fig. 2. Load histogram for TPX Macroblock.

results and converted to equivalent strain ranges using the method prescribed in the ASME B&PV Code Case N-47. The number of bakeout cycles specified for TPX was 416 together with 30,000 cycles of normal operation.

Figure 3 presents the relevant data from various authors on low cycle fatigue of OFHC at 300°C. These fatigue tests were conducted in inert environments of vacuum or argon. The dashed curve in Fig. 3 represents the best least square fitted curve for push-pull specimens with test diameters of 6.3 mm. This curve would best fit structural designs with thick copper walls which have been annealed. The solid curve in Fig. 3 represents the design fatigue curve which is based on safety margins of 2 and 20 on stress and number of cycles, respectively, for the data fitted by the dashed curve.

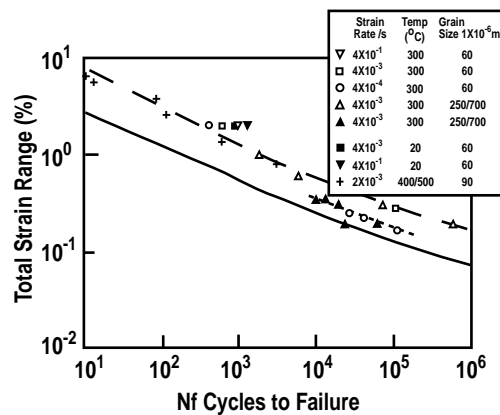


Fig. 3. Fatigue life of annealed copper in inert environment and plastic strain-range.

An estimate of the creep damage in the OFHC coolant tube was made using data from Ref. 3 as shown by Larson-Miller curves in Fig. 4. The curves were extrapolated to provide the time required for creep rupture to occur at the stress and temperature range of the coolant tube. Two possible extrapolations (curves A and B) to the low stress level are presented in Fig. 4.

A significant uncertainty in the evaluation of creep-fatigue damage is whether or not creep strain in compression is damaging in this material. In the majority of materials, it is not. In the calculations summarized, creep in compression has been conservatively assumed to be as damaging as creep in tension. This is particularly significant because, in the configuration investigated, the only elevated temperature hold periods (when creep may occur) are predicted when the stresses are compressive and cracks from creep damage would not be expected to initiate and grow in this constrained situation. The creep effects may indeed be small as indicated by the very small changes in the overall stress history obtained when creep was included in the OFHC material model. At both the bakeout and operating temperatures, the stress levels are low. However, the preliminary extrapolated creep rupture data used, predict very low allowable stresses. No design factor was used on the creep rupture data since the extrapolation was so uncertain.

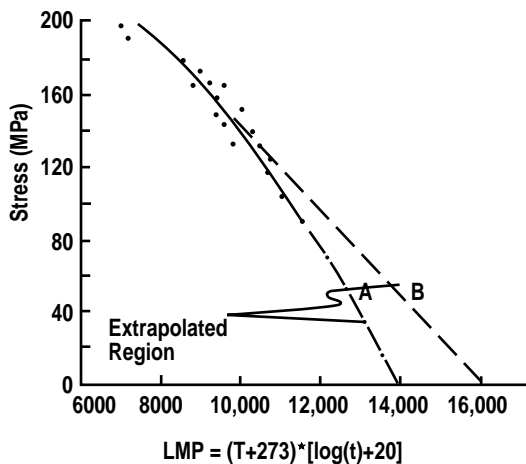


Fig. 4. Creep rupture data for OFHC (ASTM STP 181).

The combined effects of creep and fatigue were evaluated against the linear creep-fatigue damage rule for stainless steel in the ASME code case N-47. In this case, when the damage contribution from the two phenomena (creep and fatigue) are of similar magnitude the combined usage factor is limited to about 0.3. When the contribution from either is insignificant, the usage factor for the other may approach 1.0.

4. ANALYTICAL RESULTS

Figure 5 shows a typical stress/strain diagram obtained from the analysis. The stress component illustrated in the figure is the hoop stress at a point within the wall of the tube near the braze connection to the carbon. The diagram is typical of all hoop and axial stress/strain components in the tube and is used here for illustration purposes. The actual values of strain used to calculate fatigue damage at the inside and outside surfaces of the tube were obtained by combining component strain ranges to give an equivalent strain range as defined above. The effective stress (Von Mises) was used to compute creep damage.

The average hoop stress in a coolant tube during the 24 hour bakeout at 350°C is 13 MPa. The total duration for the 416 bakeout cycles specified for TPX is approximately 10,000 hours. The creep

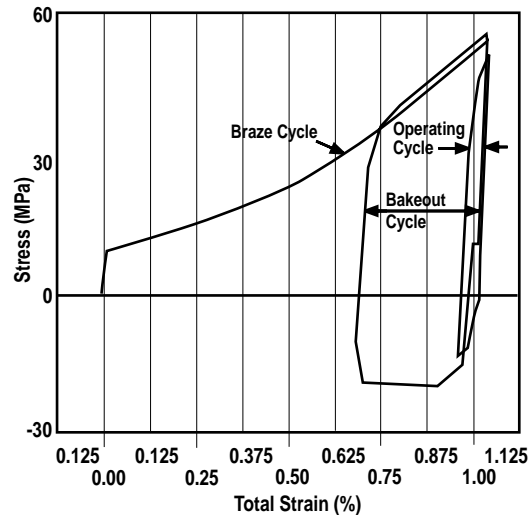


Fig. 5. Stress-strain behavior of OFHC at top of coolant tube.

rupture time corresponding to 13 MPa from extrapolated curve A in Fig. 4 is only 98 hours. Use of its value yields an unacceptable high value of creep damage. The creep rupture time obtained using curve B is 7.58×10^4 hours and results in a creep damage factor of 0.13. Clearly, the estimated creep damage is very sensitive to the method of extrapolation of the Larson-Miller curve and more long term creep data are needed to confirm the acceptability of the bakeout load cycles. The estimated creep damage due to operational cycles is negligible.

The cyclic effective strain ranges at the inside surface and at the interface with the C-C material over a bakeout cycle are 0.86 and 0.67 percent respectively. Using the design fatigue curve (Fig. 4), the allowable number of bakeout cycles is only 160 for the inside of the tube. Based on the specified number of cycles, the fatigue usage factor for this location is therefore 2.60. During operating cycles, the effective strain range at the inside of the coolant tube is only 0.05 percent from the through-the-wall thermal gradient. The effective strain range at the C-C interface is 0.18 percent for which the allowable number of cycles is 35,000 yielding a fatigue damage usage factor of 0.86. The point at the inside of the coolant tube is therefore the location where a crack is predicted to be first initiated. It should be noted that failure of the coolant tube will not occur until the flaw grows to a critical size or progresses right through the tube wall.

To ensure an adequate design margin with a total creep damage factor of 0.13, the summation of the fatigue damage usage factors must be less than 0.77 per the guideline of ASME Code Case N-47 for stainless steel. To satisfy these combined creep-fatigue criteria, the specified lifetime of the TPX brazed macroblock divertor concept would have to be reduced to 120 bakeout cycles and 14,000 cycles of steady-state operation.

High heat flux tests at 25 MW/m^2 were recently performed by JAERI on C-C saddleblock tile specimens (Ref. 4). The temperature of the top of the OFHC coolant tube reached 400°C during the test cycle, similar to bakeout conditions for the TPX macroblock concept. After 1200 thermal cycles, a water leak in the coolant tube was observed. Inspection of failure zone showed that the crack started at the inner top of the coolant tube and

propagated toward the C-C interface as well as circumferentially. The vast majority of high heat flux tests on PFCs are terminated after 1000 cycles, far short of the expected lifetimes of the component. Reference 8 and the results presented in this paper support the requirement for extended numbers of cycles in testing high heat flux PFCs.

5. CONCLUSIONS

Although annealed OFHC coolant tubes provide an excellent heat sink for HIP brazed C-C PFC tile concepts, the low creep-fatigue strength of OFHC does not provide adequate lifetimes for divertor designs of present day tokamaks. The results of this analysis show that, for TPX requirements, there was inadequate margin of safety against creep-fatigue for the preferred divertor concept. The use of OFHC for TPX would have required replacement of the divertor modules after 120 bakeout cycles at 350°C and 14,000 cycles of steady-state operation. These results indicate that a copper alloy with greater creep-fatigue properties than OFHC, but still acceptable for HIP brazing to C-C tiles, is required for high heat flux PFCs.

Although the creep stress level in the OFHC coolant tube is much lower than that for which data is available, use of extrapolated data yields high creep damage levels in the TPX macroblock divertor concept. From this analysis it is clear that an adequate design of divertor coolant tube system for a present day tokamak requires careful consideration of creep-fatigue phenomena based on custom-generated materials data.

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