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Thermal fatigue experiment of screw cooling tube under one-sided heating condition

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Abstract

This paper presents the results of thermal fatigue experiments of a cooling tube with a helical triangular fin on its inner cooling surface, namely a screw tube. The screw tube is directly machined in a CuCrZr heat sink bar with slits at its heated side. The thermal fatigue experiments are carried out at 20 and 30 MW/m^2. Water leakages from fatigue cracks, found at the slit of the heat sink, occurred at around 4500th and 1400th cycles at 20 and 30 MW/m^2, respectively. These results show good agreement with lifetime predictions using Manson–Coffin's law based on finite element analyses. Fractographic observations show the fatigue cracks starting from the outer heated surface at the slit region of the cooling channel and propagating toward its inner surface.

1. Introduction

As part of development of high heat flux components (HHFCs) for fusion machines, JAERI has developed high performance cooling tubes with pressurized water flow. Along this line, a cooling tube with helical triangular fins on its inner surface has been proposed recently [1]. Since the fin can be machined by simple threading, this tube is called a screw tube. In our previous experiments, it was found that heat removal performance of such a screw tube is twice higher than that of a smooth tube. Although the screw tube has superior heat transfer properties, it is not presently considered as a reference concept for the ITER divertor because the screw geometry potentially acts as a crack initiator as pointed out by Raffray et al. [2]. To evaluate its practical application to HHFCs, its thermo-mechanical behavior, especially thermal fatigue, has been investigated under one-sided heating conditions relevant to fusion machines.

Thermal fatigue experiments of the screw tube are carried out by using the screw tube made of CuCrZr (a candidate material of the ITER divertor cooling tube). By using finite element analyses, thermo-mechanical behavior of the screw tube is investigated to predict lifetime. After the experiments, fractographic observations are made to examine crack propagation inside the tube wall.

2. Experimental study

Test samples are screw tubes with M10 of 1.5-mm-pitch, which is based on the ISO 261 standard screw thread design, as shown in Fig. 1. The screw tube with this geometry has the highest incident critical heat flux, one of indexes for heat transfer limit of a cooling tube, obtained in the previous experimental campaign compared with other tubes [1]. Two kinds of the test samples are provided for the present experiments; one is for measuring thermal response of the test sample to verify the numerical modeling and the others are for the thermal fatigue tests. In both samples, the M10 thread is directly machined on a CuCrZr heat sink bar to form a cooling channel. Slits with the width of 1.5 mm are machined on the heated side of the heat sink to simulate

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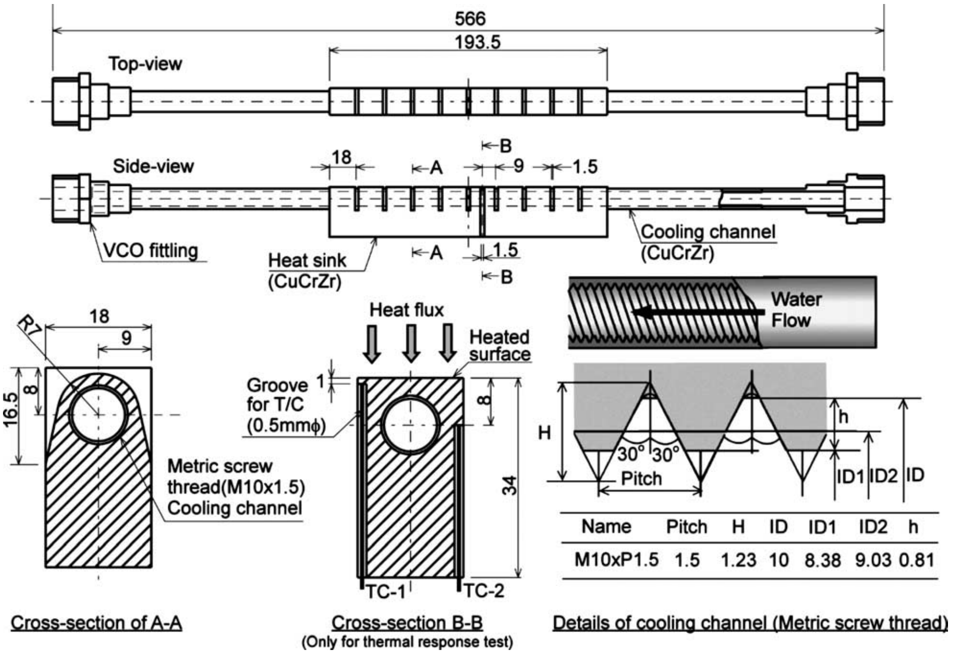

Name	Pitch	H	ID	ID1	ID2	h
M10xP1.5	1.5	1.23	10	8.38	9.03	0.81

Fig. 1. Schematic drawing of a screw tube test sample for thermal fatigue tests.

divertor geometry. The channel wall thickness at the thinnest point is 2 mm. The lower part of the heat sink remains monolithic, which prevents the cooling channel from expanding in the axial direction during heating. This geometry is considered the most severe one for the cooling channel because thermal stress and strain locally concentrate. In the test sample, where thermal response is measured, two sheathed thermocouples are attached to the sidewalls of the heat sink as shown in Fig. 1 (B–B cross-section).

The thermal fatigue experiments have been carried out at the repetitive incident heat fluxes of 20 and 30 MW/m^2 by using an electron beam irradiation facility in JAERI, JEBIS [3]. These heat flux conditions are set above the ITER divertor design values to simulate the transient plasma conditions [4]. Heating and cooling durations are 10 s to make the test sample thermally steady state. Cooling-water temperature and pressure are 25 °C and 1 MPa. Axial flow velocity of the coolant is 10 m/s.

3. Numerical analysis

To simulate the stress–strain behavior of the test sample under the thermal fatigue experimental conditions, 3-D thermo-mechanical analyses are performed using a finite element method (FEM) code, ABAQUS [5]. The strain amplitudes obtained in the analyses are used to evaluate fatigue lifetime of the test samples.

A finite element (FE) model of the test sample and boundary conditions for the analyses are shown in Fig. 2. In this model, the fins are individually crossed at right angle to the flow direction, although the actual M10 thread crosses at the angle of 86.7° to the flow direction. This difference of the angles between has little effect on the results of thermal analyses since the difference of the

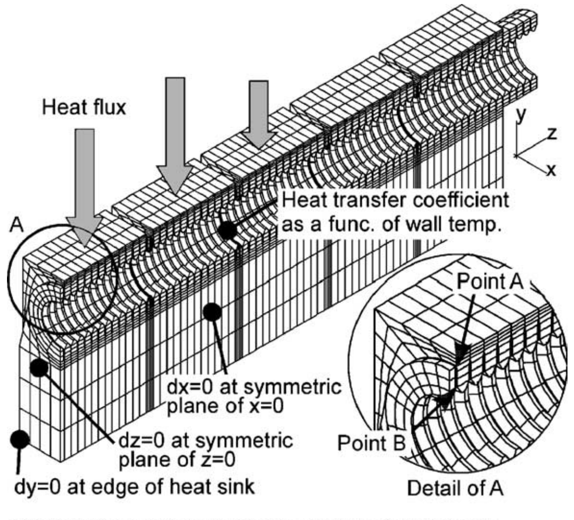

Fig. 2. Three dimensional finite element model and boundary conditions for thermal and stress analyses of the test sample.

surface area between them is very small. Roots of the fins are set under the slits.

Based on the temperature histories obtained from the transient thermal analyses, subsequent elasto-plastic stress analyses are performed, in which six thermal cycles are simulated to observe the saturated stress–strain behavior of the model. The heating and cooling durations, and the cooling water conditions are the same as the experimental ones. Heat transfer coefficient at the inner wall of the cooling channel is treated as a function of the wall temperature, which is almost twice higher than that of a smooth tube with the same hydraulic diameter in the forced-convective heat transfer regime [6]. The heat flux distributions are based on the experimental values, in which the maximum heat fluxes are 20 and 30 MW/m^2. Radiative cooling from the surfaces of the test sample is taken into account. Thermal and mechanical properties of CuCrZr depend on the temperature, which are available in Ref. [7]. Temperature dependent stress–strain relation of CuCrZr is assumed to follow a bi-liner curve. Kinematic hardening law is used for CuCrZr to simulate cyclic loading.

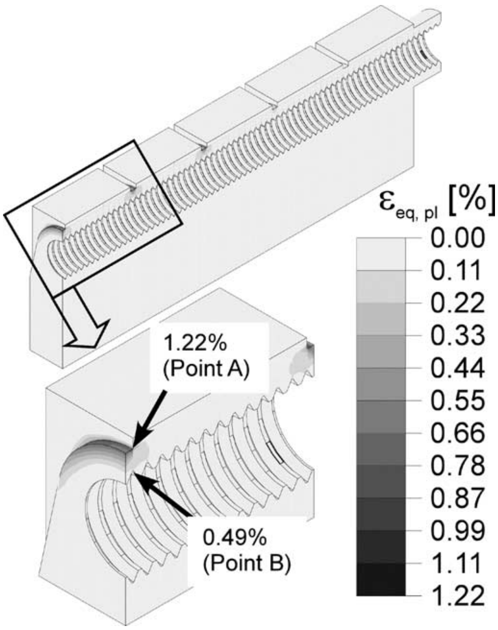

Fig. 4. Contour map of magnitude of equivalent plastic strain, $\varepsilon_{eq,pl}$, of the test sample at the end of sixth heating cycle of 20 MW/m^2.

4. Results and discussion

4.1. Thermo-mechanical analyses

To verify the numerical model of the test sample, Fig. 3 shows comparison of temperature histories measured by using the thermocouples with the numerically calculated steady-state values of 20 MW/m^2. As shown, analytical results of the maximum temperatures are in good agreement with the experimental ones. This shows that the numerical model correctly predict thermal response of the test sample.

Based on the predicted thermal responses for six thermal cycles, the elasto-plastic stress analyses are carried out under the thermal cycles. In the analyses, large deformations are observed in the slit regions of the cooling channel. Fig. 4 shows contour maps of magnitude of equivalent plastic strain, $\varepsilon_{eq\ pl}$, at the end of the sixth heating period of 20 MW/m^2, in which the maximum value of $\varepsilon_{eq\ pl}$ is 1.2% at the top heated surface of

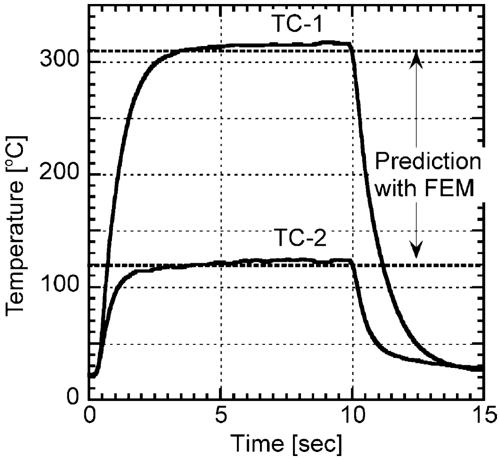

Fig. 3. Comparison of temperature evolutions measured by using the thermocouples TC-1 and TC-2 with maximum values predicted by the FEM analysis at 20 MW/m^2.

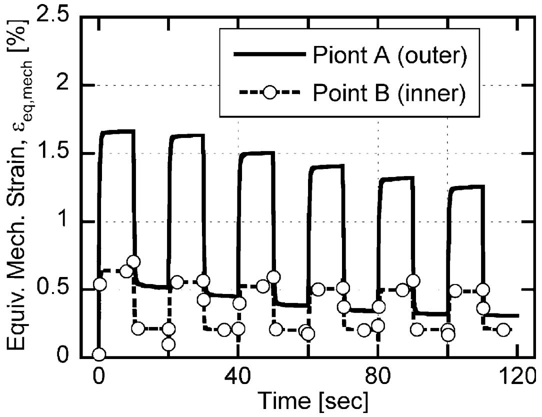

Fig. 5. Equivalent mechanical strain evolution for six thermal cycles at the outer surface of the screw tube in the slit (as indicated by Point A in Fig. 2) and at the root of the screw thread (Point B in Fig. 2).

the cooling channel in the slit (as indicated as ‘Point A’ in Fig. 2). In the root of the thread (‘Point B’), $\varepsilon_{\mathrm{eq,pl}}$ is less than 0.5%. At these points, evolutions of equivalent mechanical strains, $\varepsilon_{\mathrm{eq,mech}}$, for the six thermal cycles are shown in Fig. 5. At both points, amplitudes of $\varepsilon_{\mathrm{eq,mech}}$ become saturated after the sixth thermal cycles. The amplitude of $\varepsilon_{\mathrm{eq,mech}}$ at Point A in this cycle is 0.95 %, which is three times larger than that at Point B. The FEM analysis under the condition of 30 $\mathrm{MW/m^2}$ shows similar results as described above and the amplitude of $\varepsilon_{\mathrm{eq,mech}}$ at Point A is 1.4 %. This leads us to suspect that cracks at the tube wall in the slit region start from the outer heated surface.

4.2. Thermal fatigue experiments and fractographic observations

Water leakages from fatigue cracks, which locate at the slit of the heat sink, occurred at around 4500th and 1400th cycles at 20 and 30 $\mathrm{MW/m^2}$, respectively. These numbers of cycle to failure, N_{f}, are plotted in the Fig. 6 with respect to FEM calculated mechanical strain ranges, $\Delta\varepsilon_{\mathrm{eq,mech}}$. In this figure, the experimental results are compared with lifetime evaluation of predicted by Manson–Coffin’s law[8]. In this law, N_{f} is correlated to $\Delta\varepsilon_{\mathrm{eq,mech}}$ using the following equation:

$$\Delta\varepsilon_{\mathrm{eq,mech}} = 3.5\left(\frac{\sigma_{\mathrm{UTS}}}{E}\right)N_f^{-0.12} + \ln\left(\frac{1}{1-RA}\right)^{0.6} N_{\mathrm{f}}^{0.6}, \quad (1)$$

where σ_{UTS} is the ultimate tensile strength, E is Young’s modulus, and RA is the reduction area. These values of CuCrZr are available in Ref. [7]. The lifetime evaluations by using Eq. (1) are done in the different temperatures at 25 and 400 °C, which covers the temperature range of the cooling channel. As shown in Fig. 6, the lifetime predictions using Manson–Coffin’s law based on the FEM analyses results show good agreement with the experimental results.

To examine which surface of the cooling channel, the heated outer or the inner cooling surfaces, the fatigue cracks started from, fractographic observations are made. Fig. 7 shows Scanning Electron Microscopy (SEM) images of a fracture surface at the water-leakage point of the cooling channel after the experiments at 20 $\mathrm{MW/m^2}$; (a) is a whole cross-section of the fracture surface and (b) an enlargement of the circles in (A). Clear evidence of fatigue damage is found in the outer side of the fracture surface as shown in Fig. 7(a). On the contrary, in the inner side, ductile fracture is observed, which is a ligament of the cooling channel torn to make observations. From these results, the fatigue crack starts from the outer surface and propagates toward the inner surface. The fracture surface found at the other test sample, which has exposed to 30 $\mathrm{MW/m^2}$ thermal cyclic conditions, shows similar fracture pattern.

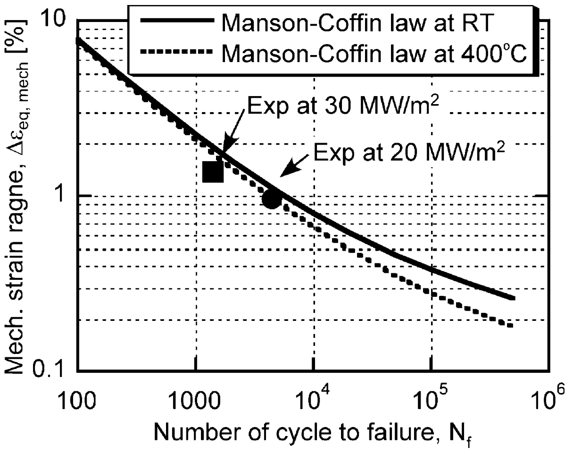

Fig. 6. Comparison of the number of cycle to failure of the test sample with lifetime evaluations by using Manson–Coffin’s law.

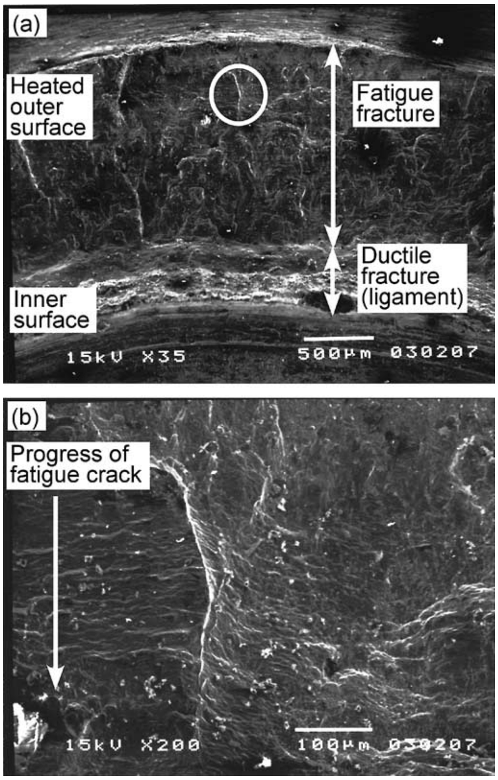

Fig. 7. Fracture surface of the test sample after thermal cycles at 20 $\mathrm{MW/m^2}$. (a) Whole cross-section of the fracture surface. (b) Enlargement of the circle in (a).

5. Conclusion

To evaluate its practical application to HHFCs, thermo-mechanical behavior of a screw tube made of

CuCrZr, especially thermal fatigue, is studied under high heat flux conditions relevant to fusion machines. In the test sample used here, the screw thread is directly shaped in a CuCrZr heat sink bar as the cooling channel. Slits of 1.5 mm wide are machined at the heated sides of the heat sink. The lower part of the heat sink remains monolithic, which prevents the cooling channel from expanding in the axial direction during being heated.

Thermal cycling tests on the test samples are carried out under the one-sided heated condition of 20 and 30 MW/m^2. Water leakages from fatigue cracks, which locate at the slit of the heat sink, occurred at around 4500th and 1400th cycles at 20 and 30 MW/m^2, respectively. These numbers of cycle to failure can be predicted by the lifetime estimation by using Manson–Coffin's law assisted by thermo-mechanical analyses. The thermo-mechanical analyses and fractographic observations reveal that fatigue cracks start from the heated outer side and propagate toward the inner surface. This indicates that the screw geometry does not act as a crack initiator under the one-sided heated condition with high heat flux appearing in divertors for fusion machines. To elongate the thermal fatigue lifetime needs reduction of stress and deformation concentration in the cooling channel. For this purpose, a sliding rail support such as a dovetail geometry taken in ITER divertor is considered to be effective. Based on these results it turns out that the screw tube can offer promise of a high performance cooling structure for a divertor plate.

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