Impact of plastic softening of over-aged CuCrZr alloy heat sink tube on the structural reliability of a plasma-facing component

M. Miskiewicz [(a)] and J.-H. You* [(b)]

[a)] Department of Materials Science & Engineering, Warsaw University of Technology, Woloska 141 02-564 Warsaw, Poland

[b)] Max-Planck-Institut für Plasmaphysik, EURATOM Association, Boltzmannstr. 2, 85748 Garching, Germany

Abstract

Precipitation-hardened CuCrZr alloy is used in fusion experiments as heat sink material for water-cooled plasma-facing components. When exposed to long term high-heat-flux (HHF) plasma operation, CuCrZr will undergo over-ageing and thus plastic softening. In this situation the softened CuCrZr heat sink tube will suffer from substantial plastic straining and thus fatigue damage in the course of the cyclic HHF loads. In this paper a computational case study is presented regarding the cyclic plasticity behaviour of the over-aged CuCrZr cooling tube in a water-cooled tungsten mono-block divertor component. Finite element analysis was performed assuming ten typical high-heat-flux load cycles and using the Frederick-Armstrong constitutive equation together with corresponding material parameters. It was shown that plastic shakedown and low cycle fatigue (LCF) would be caused in the heat sink tube when softening of CuCrZr should occur. On the other hand, neither elastic shakedown nor cumulative plastic strain (ratchetting) was found. LCF design life of the CuCrZr tube was estimated based on the ITER materials handbook considering both hardened and softened states of CuCrZr. Substantial impact of softening of the CuCrZr alloy on the LCF lifetime of the heat sink tube was demonstrated.

* : Corresponding author

Phone: ++49 89 3299 1373

e-mail address: you@ipp.mpg.de

1. Introduction

In designing an actively cooled plasma-facing component (PFC) for fusion reactors, heat removal capability is an essential design concern [1, 2]. Precipitation-hardened copper alloy, CuCrZr is currently considered to be a favoured candidate material for the heat sink of PFCs due to its excellent thermo-physical and thermo-mechanical behaviour [3]. On the other hand, soft copper is considered as material for the stress-relieving bond interlayer (e.g. braze) between the armour material and the heat sink where thermal stresses concentrate due to the thermal expansion mismatch.

In the course of cyclic high-heat-flux (HHF) loading, the copper alloy heat sink as well as the copper interlayer will suffer from repeated plastic deformation. Especially, the soft copper interlayer is expected to experience severe incremental plastic straining due to the small yield stress [4].

In the case of the CuCrZr heat sink, the problem of plastic deformation will not be so acute, provided that the original yield strength of the initially hardened alloy persists. However, the precipitation hardened CuCrZr alloy will undergo over-ageing resulting in plastic softening when it is exposed to a long term HHF operation. In viewpoint of plastic stability such change is detrimental, since intensified plastic strain amplitude can be caused.

Repeated thermal stress variation can generate either cumulative plastic strains or plastic shakedown (alternating plasticity) [5]. The progressive accumulation of plastic strains will lead to incremental plastic collapse (ratchetting) whereas the plastic shakedown causes low cycle fatigue (LCF) damage. In order to identify the plastic failure mechanism and to assess the structural lifetime under cyclic HHF loads, accurate computation of plastic strain history is required. To this end, a proper constitutive equation of cyclic plasticity is needed. In addition, experimental data for the corresponding material parameters are required too. Recently, complete set of the material parameters were obtained by authors both for soft copper and for CuCrZr alloy in terms of the Frederick-Armstrong model for temperatures ranging from 20 °C to 550 °C [6]. Parameters of softened as well as of hardened CuCrZr were experimentally identified.

The aim of this paper is to demonstrate the impact of the cyclic plasticity behaviour of CuCrZr heat sink as well as copper interlayer on the structural reliability of a PFC. We present a computational case study based on the finite element analysis (FEA) for a water-cooled tungsten mono-block PFC assuming a typical fusion relevant heat flux load and using the Frederick-Armstrong material model.

2. FEA model

2.1. Geometry, materials and mesh

The model PFC considered for the FEA study was the water-cooled tungsten mono-block duplex structure consisting of tungsten armour hexahedra and a CuCrZr alloy coolant tube (heat sink). Geometry and constituent materials of the considered model PFC are illustrated in Figure 1 for the symmetric half. The reference of this model was the water-cooled divertor design of the European Power Plant Conceptual Study (PPCS model A, WCLL) [2]. The heat sink tube had a thickness of 1 mm and a diameter of 10 mm. The thickness of the copper interlayer, which was 0.5 mm, was chosen rather arbitrarily. Commercial FEA code ABAQUS was employed for the simulation [7]. Linear reduced 3-d continuum elements were used.

In Table 1, the selected material properties used for the FEA are listed with short descriptions [6, 8]. Two distinct heat treatment states of CuCrZr were considered, namely, the precipitation-hardened (PH) and the annealing-softened (AS) CuCrZr. The AS CuCrZr was incorporated to consider softening effect to be caused by over-ageing. The Frederick-Armstrong constitutive model applied for copper and CuCrZr alloy is based on the combination of non-linear isotropic and non-linear kinematic hardening laws [9-11]. Details of this model are described in Appendix. The complete data of the cyclic plasticity parameters used for whole simulation temperature range (from 20 °C to 550 °C) will be published elsewhere [6]. The yield stresses given in Table 1 are essentially smaller than the literature values [8]. This is due to the fact that the yield stresses reported in [6] were obtained from a numerical data fitting process whereas the literature data were determined by 0.2 % offset method.

2.2. Loads and boundary conditions

The thermal history of the model PFC considered for simulation includes fabrication process and pre-heating step as well as the HHF load cycles. The assumed thermal load history is summarised in Table 2. The stress-free temperature was assumed to be 900 °C, which would correspond to the joining temperature. Subsequently, the heat treatment process for precipitation hardening was simulated. For the uniform heating from RT to 450 °C the plastic parameters of the AS CuCrZr was used for the coolant tube whereas the parameters of the PH CuCrZr was assumed for the cooling step. The next temperature change step was uniform pre-heating of the PFC to 300 °C. This simulates the pre-heating step by pressurised hot coolant water. Finally ten HHF load cycles were simulated. The assumed parameters for the HHF load cycles are listed in Table 3. These values correspond to a load condition expected for power reactors [2]. The first five cycles were computed using the PH CuCrZr whereas the rest five cycles using the AS CuCrZr. The switching of the material parameters from the former to the latter corresponds to softening of the PH CuCrZr caused by over-ageing. The peak temperature of the heat sink tube reached 468 °C.

The displacement of the edge cross sections of the coolant tube and of the interlayer were fully constrained in the tube axis direction.

3. Simulation results and discussion

In Figures 3 and 4, the thermal stresses generated in the copper interlayer and in the CuCrZr cooling tube are presented, respectively. Circumferential stress component perpendicular to the symmetry cut plane (x-direction) is plotted for the positions indicated in figure 2 with solid and open circles. Conspicuous cyclic variation of the stresses is shown. Mean stress was shifted by the softening of the tube. The stress range and the mean stress at the same positions are summarised in Table 4. It is observed that the softening of the CuCrZr tube caused relaxation of the mean stress, especially in the CuCrZr tube. The same behaviour was observed for the tungsten armour too. This mean stress relaxation is simply a consequence of modified force equilibrium. The stress amplitude in the CuCrZr tube was notably reduced after the softening, while it remained nearly unchanged in the copper layer.

In Figure 5 the evolution of the plastic strains of the copper interlayer (at the solid circle position) are plotted for the HHF load cycles. Each curve denotes one of the plastic strain components in a cylindrical coordinate system, respectively. All three plastic strain components showed cyclic variation with saturating amplitudes. This feature clearly indicates a LCF situation (i.e. plastic shakedown). Cumulative plastic strain was nearly negligible (no ratchet strain).

In Figure 6 the evolution of the plastic strains of the CuCrZr cooling tube (at the open circle position) are plotted. During the first five cycles the tube with hardened state showed slight and nearly monotonic relaxation of plastic strains. During the latter five cycles, when softening was introduced, the plastic strains of the tube showed distinct

LCF behaviour with substantial amplitudes. Both the amplitude and the magnitude of the plastic strains were readily saturated indicating LCF behaviour. Such remarkable change in the plastic straining behaviour clearly implies the impact of softening on the LCF lifetime.

In Figure 7 the evolution of the equivalent plastic strains at the two positions is plotted. The curves are cumulative equivalent plastic strains. In the copper layer significant plastic strains were generated during the whole load cycles. The PH CuCrZr tube showed only slight increase of plastic strains while the AS CuCrZr tube underwent substantial plastic straining which was comparable to that of copper layer. Owing to the simultaneous change in both stresses and temperature, the interplay between the cyclic strain hardening and the concurrent thermal softening played an essential role in the stabilisation of the strain cycles [12]. The increments of the equivalent plastic strains are listed in table 5. The increment of the equivalent plastic strain reached saturation within a few load cycles, as was expected in Figures 5 and 6.

From these results it is concluded that if the plastic softening of the over-aged CuCrZr tube becomes essential, LCF will be a crucial design concern. In this context, LCF lifetime of the tube and of the interlayer was estimated using the fatigue design curve data recommended in the ITER Material Properties Handbook [13]. The estimated number of allowed load cycles is given in Table 5. It should be noted that the ITER fatigue design curves are valid only for temperature range from 20 °C to 350 °C, which is below the current temperature range of interest. Furthermore, the fatigue design life of the AS CuCrZr tube was calculated using the data of copper. Therefore, this conservative result provides only a rough guideline for the fatigue life.

The estimated fatigue life of the PH CuCrZr tube exceeded the required design limit by far as long as the precipitation hardening was conserved. On the contrary, the AS CuCrZr tube revealed significant LCF behaviour and thus strong reduction in the fatigue life which was far from the lifetime required for a PFC of a commercial reactor. The copper interlayer showed the most severe LCF and thus the shortest fatigue life even less than 200 cycles. This reveals the essential weakness of copper in terms of structural performance. The LCF feature demonstrated that the plastic softening of the CuCrZr heat sink tube causes indeed serious lifetime reduction.

In Figure 8, the influence of the applied hardening laws on the plastic strain evolution in the CuCrZr heat sink tube was demonstrated. Equivalent plastic strains computed with the two material models, namely, non-linear combined hardening and non-linear isotropic hardening were compared. The distinct difference in the predicted plastic strains exhibits the essential contribution of the kinematic hardening. Thus, this result demonstrates the importance of a proper constitutive equation in the assessment of LCF behaviour.

Summary

In this paper a FEM based computational case study was presented regarding the cyclic plasticity behaviour of the over-aged CuCrZr heat sink tube and of the copper bond interlayer in a water-cooled plasma-facing component. The effect of the plastic softening of the over-aged CuCrZr heat sink tube was investigated considering the reference geometry taken from the tungsten mono-block divertor design of the PPCS model A. Finite element analysis was performed assuming fusion-relevant high-heat-flux load cycles and using the Frederick-Armstrong constitutive equation.
Substantial low cycle fatigue behaviour was identified for both the copper layer and the softened CuCrZr tube. Fatigue lifetime was estimated using the fatigue design curves of the ITER database. Strong reduction of the low cycle fatigue lifetime was predicted in the case of the softened CuCrZr tube in comparison to hardened alloy tube. This feature demonstrated the importance of softening problem with regard to structural reliability of a PFC under cyclic heat flux loads.

Appendix

Considering asymmetric hardening the von Mises yield criterion is given by

$$F = \left[\frac{3}{2}(S - \alpha') : (S - \alpha') \right]^{0.5} - \sigma_e(\varepsilon_e^{pl}) = 0$$

where F is the plastic potential in the sense of the associated flow rule, S the deviatoric stress tensor, α' the deviatoric backstress tensor, σ_e the equivalent stress and ε_e^{pl} the equivalent plastic strain. The backstress tensor α stands for the yield surface displacement in a stress space whereas σ_e indicates the size of the yield surface.
The non-linear kinematic hardening law is expressed as [3]

$$\dot{\alpha} = \frac{C}{\sigma_e}(\sigma - \alpha)\,\dot{\varepsilon}_e^{pl} - \gamma\,\alpha\,\dot{\varepsilon}_e^{pl}$$

where $\dot{\alpha}$ is the backstress rate tensor, C is the initial kinematic hardening modulus, $\dot{\varepsilon}_e^{pl}$ is the equivalent plastic strain rate and γ is the constant determining the rate at which the kinematic hardening modulus decreases with increasing plastic strain. C and γ are material parameters to be calibrated.

The first term is the contribution of the Ziegler's linear kinematic hardening and the second one is the non-linear relaxation term.

The non-linear isotropic hardening law is expressed as

$$\sigma_e = \sigma_o + Q \cdot [1 - \exp(-b \cdot \varepsilon_e^{pl})]$$

where σ_o is the initial size of the yield surface, Q the maximum change in the size of the yield surface and b defines the rate at which the size of the yield surface changes as plastic straining progresses. Q and b are material parameters to be calibrated.

The five material parameters of the combined nonlinear hardening law are calibrated by fitting method using the stabilised loops of unidirectional strain controlled cyclic tension-compression tests [2].

References

[1] ITER team, ITER-FEAT Final Design Report, 2001.

[2] A Conceptual Study of Commercial Fusion Power Plants, Final Report of European Fusion PPCS, EFDA-RP-RE-5.0, 2004

[3] M. Lipa, A. Durocher, R. Tivey, Th. Huber, B. Schedler and J. Weigert, The use of copper alloy CuCrZr as a structural material for actively cooled plasma facing and in-vessel components, Fusion Eng. Des. 75-79 (2005) 469-473.

[4] J.D. Morrow, Internal Friction, Damping and Cyclic Plasticity, ASTM STP 378, 1965, p. 45.

[5] J. Lemaitre and J.-L. Chaboche, Mechanics of Solid Materials, Cambridge Univ. Press, Cambridge, 1990, p.113.

[6] J.-H. You and M. Miskiewicz, Material parameters of copper and CuCrZr alloy for cyclic plasticity at elevated temperatures, J. Nucl. Mater., to be published.

[7] ABAQUS 6.6 analysis user's manual, ABAQUS Inc, Providence, 2006

[8] ITER Structural Design Criteria for In-Vessel Components (SDC-IC) Appendix A: Materials Design Limit Data (2001)

[9] J. Lemaitre and J.-L. Chaboche, *ibid*, pp.228-240.

[10] P.J. Armstrong and C.O. Frederick, C.E.G.B. Report RD/B/N 731, 1966.

[11] J.L. Chaboche, Constitutive equations for cyclic plasticity and cyclic visco-plasticity, Int. J. Plasticity 5 (1989) 247-302.

[12] C.E. Feltner and C. Laird, Cyclic stress-strain response of F.C.C. metals and alloys, Acta Metall. 15 (1967) 1621-1632.

[13] ITER Material Properties Handbook, ITER Document No. G74 MA16, 2005.

Figure captions

Figure 1. Geometry and materials of the considered model PFC. Only the symmetric half part was modelled The reference of this model was the water-cooled divertor design of the PPCS model A [2].

Figure 2. Two selected monitoring positions on the symmetry cut plane for plotting the stress and strain data.

Figure 3. Thermal stress generated in the copper interlayer. Circumferential stress component normal to the symmetry cut plane (x-direction) is plotted for the solid circle position marked in figure 2.

Figure 4. Thermal stress generated in the CuCrZr cooling tube. Circumferential stress component normal to the symmetry cut plane is plotted for the open circle position marked in figure 2.

Figure 5. Evolution of the plastic strains of the copper interlayer (at the solid circle position) plotted for the HHF load cycles. Each curve denotes one of the plastic strain components in a cylindrical coordinate system, respectively.

Figure 6. Evolution of the plastic strains of the CuCrZr cooling tube (at the open circle position) plotted for the HHF load cycles. Each curve denotes one of the plastic strain components in a cylindrical coordinate system, respectively.

Figure 7. Evolution of the equivalent plastic strains at the solid circle and open circle positions, respectively.

Figure 8. Influence of the applied hardening laws on the plastic strain evolution in the CuCrZr heat sink tube. Equivalent plastic strains computed with the two material models were compared, namely, non-linear combined hardening law and non-linear isotropic hardening law.

Table 1. Used material properties at 400 °C [6, 8].

	Tungsten [a)]	CuCrZr [b)]	CuCrZr [c)]	copper [d)]
Young's modulus (GPa)	393	106	97	95
Yield stress (MPa)	1100	238	17	3
Values for Q (MPa), b [e)]		-68, 10	45, 50	36, 25
Values for C (MPa), γ [e)]		117500, 1023	43335, 1054	31461, 952
Heat conductivity (W/mK)	140	352	352	352
CTE (10^{-6}/K)	4.6	19.3	19.3	19.3

a): Rolled and stress-relieved state.

b): Precipitation-hardened state after heat treatment at 450 °C.

c): Over-aged and softened state after annealing at 700 °C for 1 hour.

d): Softened by annealing at 700 °C for 1 hour.

e): Reference alloy: Elmedur-X (code: CuCr1Zr, Cr: 0.8 %, Zr: 0.08 %)

Table 2. Thermal load histories considered for the simulation [2].

<table>
<tr><td>Simulated thermal operation</td><td>Assumed temperature change</td></tr>
<tr><td>Fabrication</td><td>Cooling from 900 °C to 20 °C</td></tr>
<tr><td>Heat treatment for precipitation hardening</td><td>Heating to 450 °C, cooling to 20 °C</td></tr>
<tr><td>Pre-heating with coolant flow</td><td>Heating to 300 °C</td></tr>
<tr><td>5 Heat flux load cycles with PH CuCrZr tube</td><td rowspan="2">Copper interlayer: 320 ~ 515 °C
CuCrZr cooling tube: 320 ~ 468 °C</td></tr>
<tr><td>5 Heat flux load cycles with AS CuCrZr tube</td></tr>
</table>

Table 3. HHF load parameters used for the simulation [2].

Stress free temperature	900 °C
Heat flux	15 MW/m^2
Pulse duration	30 s
Coolant temperature	320 °C
Coolant pressure	15.5 MPa
Heat transfer coefficient	0.156 MW/m^2K

Table 4. Predicted thermal stress* range and mean stress* shift.

	Copper interlayer (MPa)	CuCrZr tube (MPa)
Stress range (5^{th} cycle)	112	250
Mean stress (5^{th} cycle)	-29	-163
Stress range (10^{th} cycle)	119	177
Mean stress (10^{th} cycle)	-1	-8

*: Hoop stress component

Table 5. Predicted increments of equivalent plastic strains and design fatigue life.

	Copper interlayer	CuCrZr tube
5^{th} cycle	0.00738 (164)*	0.00032 (> 1,000,000)*
10^{th} cycle	0.00754 (157)*	0.00469 (543)*

()*: Fatigue design life (allowed number of load cycles) was estimated based on the fatigue design curves of the ITER Material Properties Handbook (for 20 °C – 350 °C).

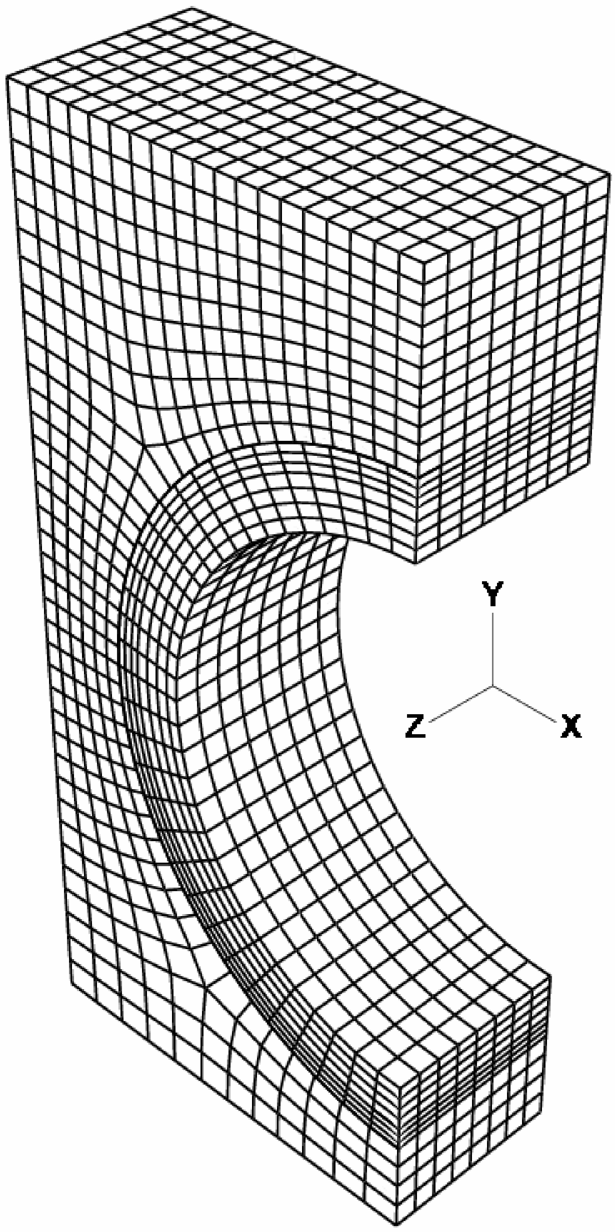


Figure 1.

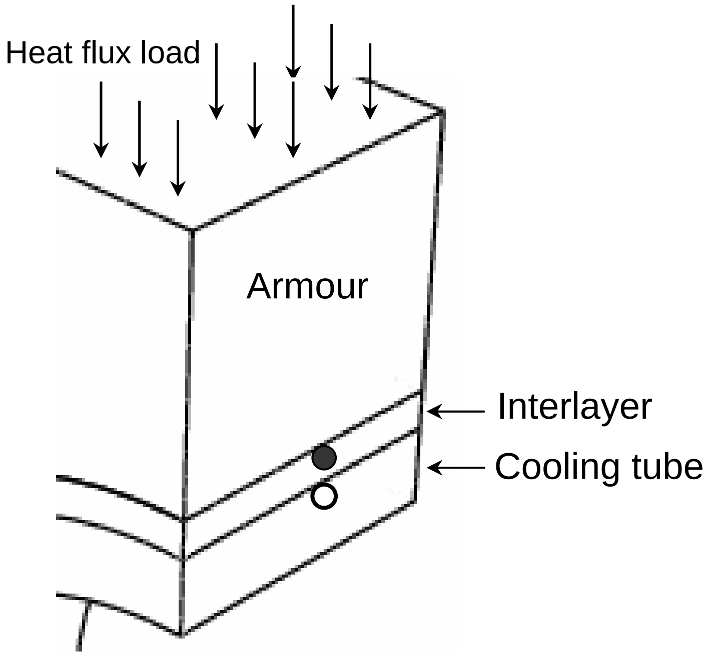


Figure 2.

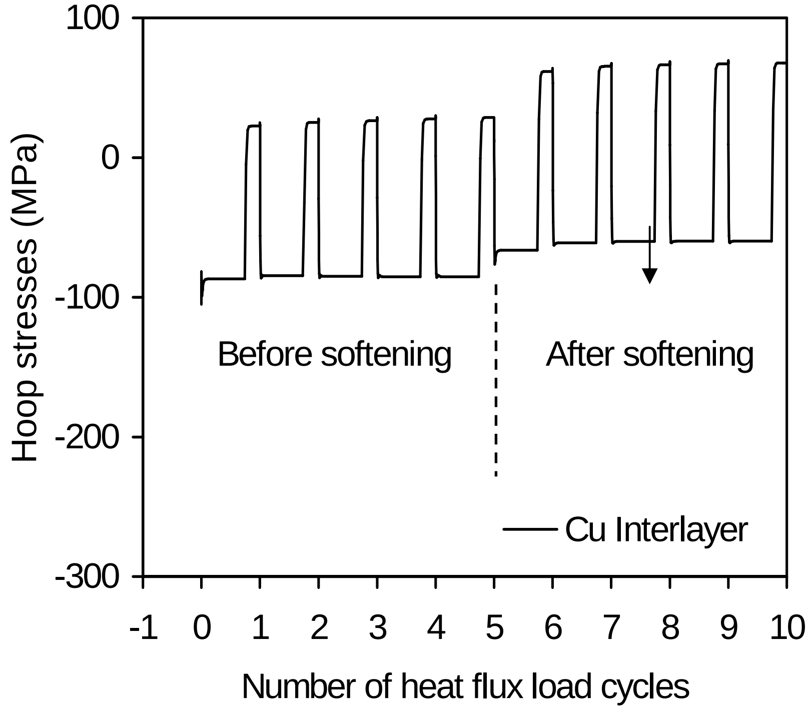

100
0
-100
-200
-300
Hoop stresses (MPa)
Before softening
After softening
Cu Interlayer
-1
0
1
2
3
4
5
6
7
8
9
10
Number of heat flux load cycles

Figure 3.

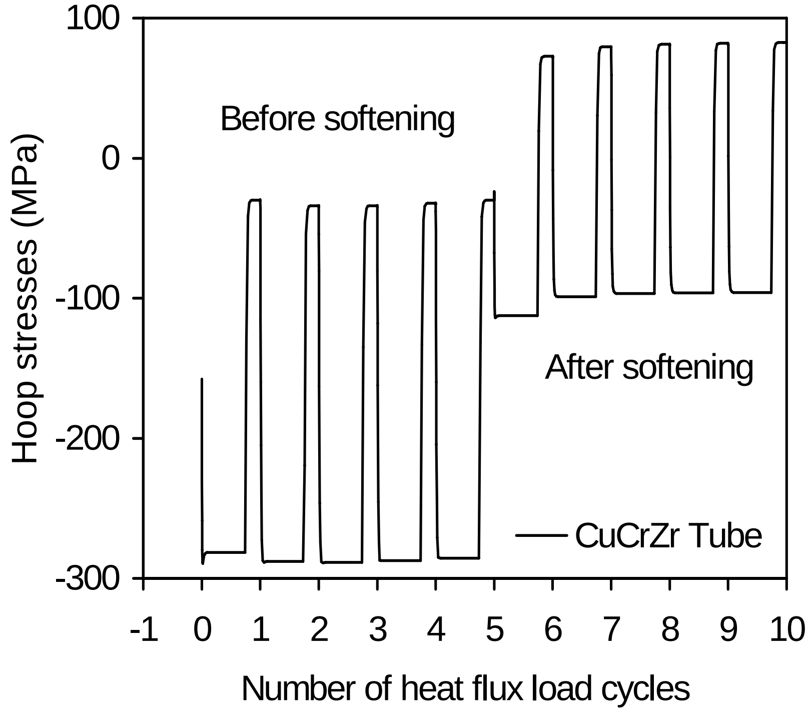

100
0
-100
-200
-300
Hoop stresses (MPa)
Before softening
After softening
CuCrZr Tube
-1
0
1
2
3
4
5
6
7
8
9
10
Number of heat flux load cycles

Figure 4.

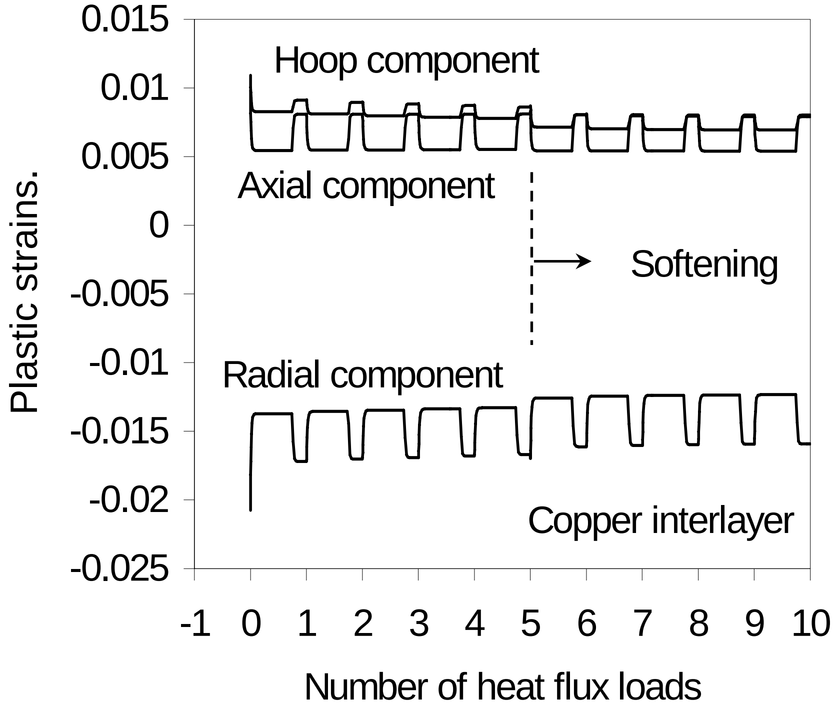
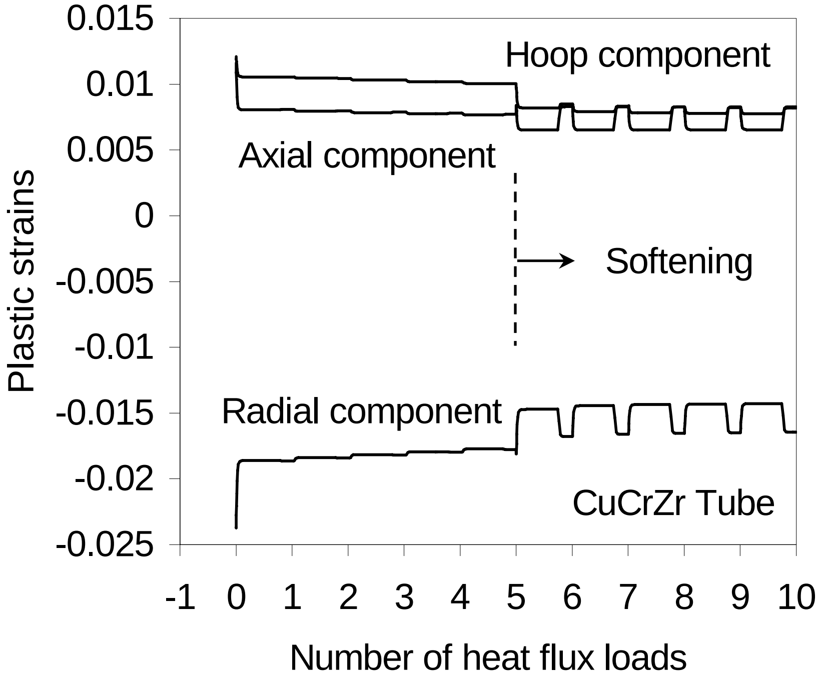

0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
-0.025
Plastic strains.
Hoop component
Axial component
Softening
Radial component
Copper interlayer
-1
0
1
2
3
4
5
6
7
8
9
10
Number of heat flux loads

Figure 5.



0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
-0.025
Plastic strains
Hoop component
Axial component
Softening
Radial component
CuCrZr Tube
-1
0
1
2
3
4
5
6
7
8
9
10
Number of heat flux loads

Figure 6.

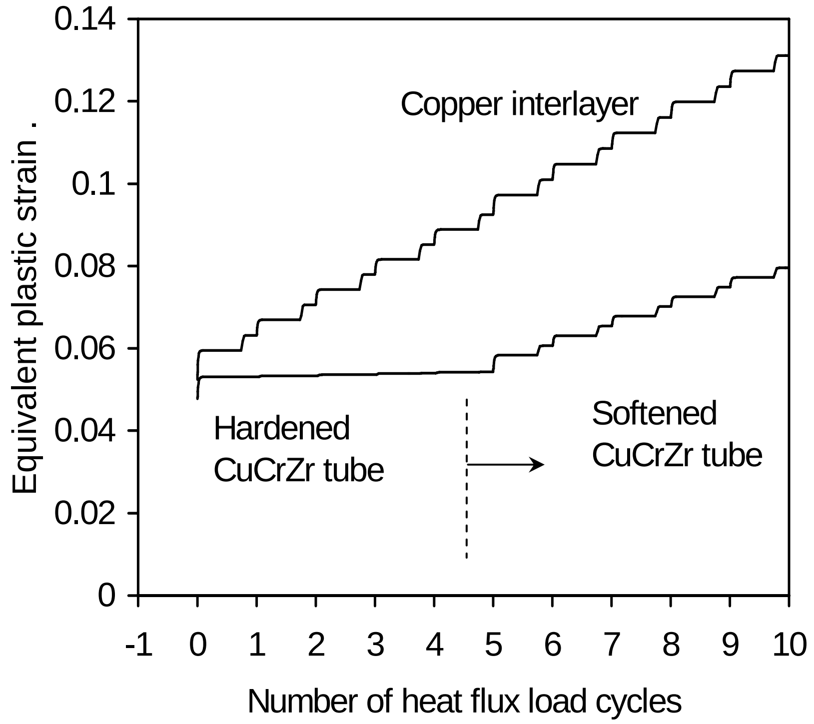

0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Equivalent plastic strain .
Copper interlayer
Hardened
CuCrZr tube
Softened
CuCrZr tube
-1
0
1
2
3
4
5
6
7
8
9
10
Number of heat flux load cycles

Figure 7.

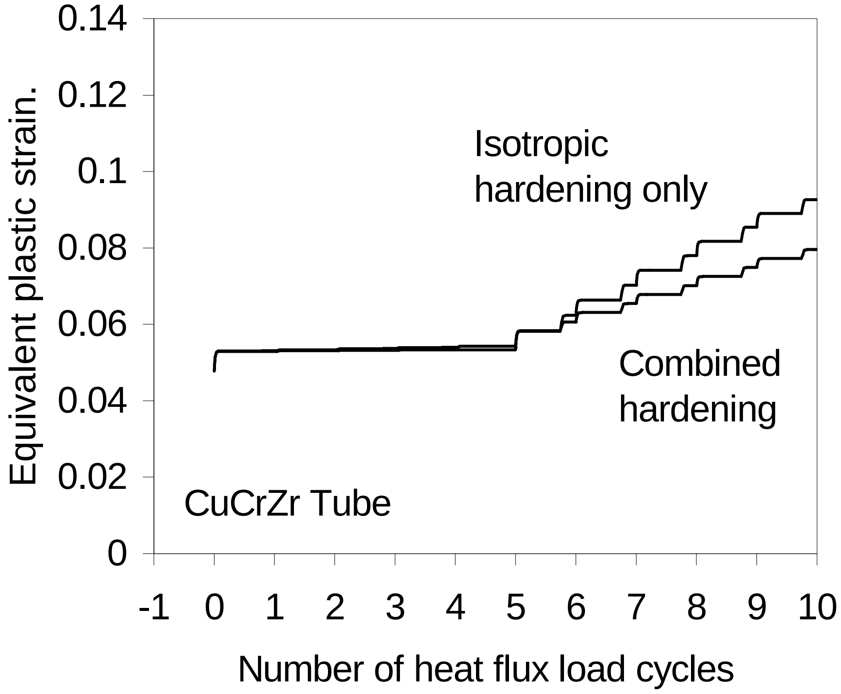

0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Equivalent plastic strain.
Isotropic
hardening only
Combined
hardening
CuCrZr Tube
-1 0 1 2 3 4 5 6 7 8 9 10
Number of heat flux load cycles

Figure 8.