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Prediction of plastic deformation of fiber-reinforced copper matrix composites

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Abstract

Copper alloys have been considered as a structural material for the heat sink of the actively cooled plasma facing components due to its high thermal conductivity. However, the decrease of strength at elevated temperatures and their large thermal expansion are detrimental aspects. The fiber-reinforced copper matrix composites (FRCMC) can be a potential candidate as heat sink material. In this article, the non-linear constitutive behavior of the FRCMCs reinforced with continuous SiC fibers is predicted. To this end, a simulation tool was developed using analytical micro-mechanics theory. The effects of thermal residual stress and of the matrix flow stress are estimated. The results show that these composites have a significantly increased work-hardening rate compared to the unreinforced matrix metals. The thermal residual stress has a marked influence on the initial yield surface as well as on the stress–strain curve showing asymmetry in tension and compression.

1. Introduction

Surface heat loads which have to be removed by the plasma facing components of a next generation fusion device (ITER) reach up to 20 MW/m^2 under quasi-stationary condition [1]. Copper alloys have been considered as a structural material for the heat sink substrate of such plasma facing components due to their high thermal conductivity [1–3]. However, the decrease of strength at elevated temperatures and large thermal expansion are detrimental aspects of these materials. Dispersion strengthening (DS) or precipitation hardening (PH) have normally been applied to achieve the required strength at the operation temperature [3].

The fiber-reinforced copper matrix composites (FRCMC) can be a potential candidate for such an application, since the combination of different material properties can generate versatile performances of these materials [4]. They can possess much higher ultimate strength, work-hardening rate and creep resistance than the conventional PH or DS alloys at high temperature. The ultimate load carrying capacity of this composite will depend either on the onset of progressive plastic flow of the matrix or on the overall fiber fracture. In addition, the elastic stiffness as well as the thermal expansion coefficient can be tailored in a wide range, which is especially advantageous for the application to bond-joint-type plasma facing components to reduce the thermal mismatch stress at the bonded interface of dissimilar materials. Permanent dimensional change during the service time can be effectively suppressed. In addition, fiber reinforcement can be introduced locally into the mostly highly loaded regions of the components.

In this work, the prediction of the thermo-mechanical properties and of the resulting non-linear constitutive behaviors for a FRCMC reinforced with continuous SiC fibers are presented. To this end, a simulation tool was developed using analytical micro-mechanics theory. The effects of thermal residual stress and of matrix flow stress are estimated.

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2. Theoretical background

Withers, Stobbs and Pedersen applied Pedersen's formulation of the Mori–Tanaka mean field scheme directly to the Tresca yield criterion to determine the instantaneous global composite flow stress [5–8]. The dynamic stress relaxation in the matrix during the plastic deformation is included in an empirical manner [9]. It is assumed that the global yielding of a FRCMC is governed only by plastic flow in the matrix. In the framework of the mean field scheme, the onset of global yielding of the FRCMC is determined by investigating whether the phase averaged total stress state in the matrix satisfies a yield condition which would give rise to flow were it experienced by the matrix material free from the reinforcement.

According to their approach, the so-called mean internal stress $\langle\sigma\rangle^{(m)}$ in the matrix and $\langle\sigma\rangle^{(i)}$ in the fiber are given by [7–9]:

$$\langle\sigma\rangle^{(m)} = -fE^{(m)}(S-I)\varepsilon^{T}_{eq}, \tag{1}$$

$$\langle\sigma\rangle^{(i)} = (1-f)E^{(m)}(S-I)\varepsilon^{T}_{eq}, \tag{2}$$

where I denotes the fourth rank identity tensor, S the Eshelby tensor, f fiber volume fraction and $E^{()}$ the stiffness matrix. The superscripts c, m and i mean composite, matrix and fiber, respectively. ε^{T}_{eq} represents the so-called equivalent transformation strain which is given by

$$\varepsilon^{T}_{eq} = -\left\{\left(E^{(m)}-E^{(i)}\right)[S-f(S-I)]-E^{(m)}\right\}^{-1} \times \left(E^{(m)}-E^{(i)}\right)E^{(m)^{-1}}\sigma_a \tag{3}$$

for applied stress σ_a,

$$\varepsilon^{T}_{eq} = -\left\{\left(E^{(m)}-E^{(i)}\right)[S-f(S-I)]-E^{(m)}\right\}^{-1} \times E^{(i)}\left(\alpha^{(i)}-\alpha^{(m)}\right)\Delta\vartheta \tag{4}$$

for differential thermal strain misfit where $d\vartheta$ is the far-field uniform temperature change, and finally

$$\varepsilon^{T}_{eq} = \left\{\left(E^{(m)}-E^{(i)}\right)[S-f(S-I)]-E^{(m)}\right\}^{-1} \times E^{(i)}\left[(1-f)^{-1}\varepsilon^{c}_{pl}\right]^{0.5} \tag{5}$$

for plastic strain misfit where ε^{c}_{pl} is the global plastic strain undergone by the composite in the direction of loading. This equation becomes inaccurate for high volume fractions ($f > 0.2$).

For simplicity, we assume that a FRMMC is loaded by an uni-axial external stress σ_a in fiber axis direction (say, axis 3). According to the Tresca yield criterion, the applied stress σ_a reaches global yield stress σ^{c}_{y}, if following condition satisfies

$$\sigma_a = \sigma^{c}_{y} = \frac{W}{P}\varepsilon^{c}_{pl} + \sigma^{(m)}_{y}, \tag{6}$$

where $\sigma^{(m)}_{y}$ is the initial yield stress of the matrix.

The coefficients P and W are defined by

$$\left\lfloor\langle\sigma_3\rangle^{(m)}_{tot} - \langle\sigma_1\rangle^{(m)}_{tot}\right\rfloor = \sigma^{(m)}_{y} - \left\lfloor\langle\sigma_3\rangle^{(m)} - \langle\sigma_1\rangle^{(m)}\right\rfloor = P\sigma_a \tag{7}$$

for the applied stress σ_a and

$$\left\lfloor\langle\sigma_3\rangle^{(m)}_{tot} - \langle\sigma_1\rangle^{(m)}_{tot}\right\rfloor = \left\lfloor\langle\sigma_3\rangle^{(m)} - \langle\sigma_1\rangle^{(m)}\right\rfloor = -W\varepsilon^{c}_{pl} \tag{8}$$

for the global plastic strain undergone by the composite ε^{c}_{pl}, respectively. $\langle\sigma_i\rangle^{(m)}_{tot}$ denotes the phase averaged total stress state in the matrix whereas $\langle\sigma_i\rangle^{(m)}$, the principal mean internal stress component in the matrix for axis i.

3. Results and discussion

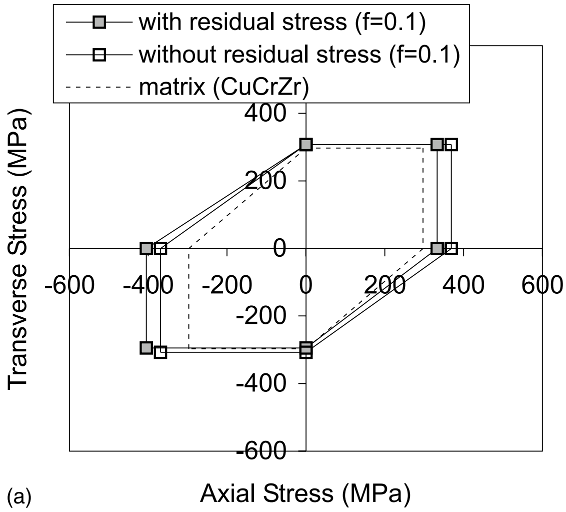
In this work, the uni-directional reinforcement of continuous fibers is assumed. Both precipitation hardened CuCrZr alloy and pure copper are chosen for the matrix. Some selected material properties of matrices and fiber are listed in Table 1.

In Fig. 1, the effective global initial yield surfaces of the two FRCMCs for $f = 0.1$ are plotted in bi-axial principal stress spaces where the abscissa denotes the stress component in fiber axis direction whereas the ordinate indicates the stress in transverse direction. Since the Tresca yield function was used for the criterion of matrix flow, the yield surfaces of the composites and of the matrices show a polygonal isomorphism.

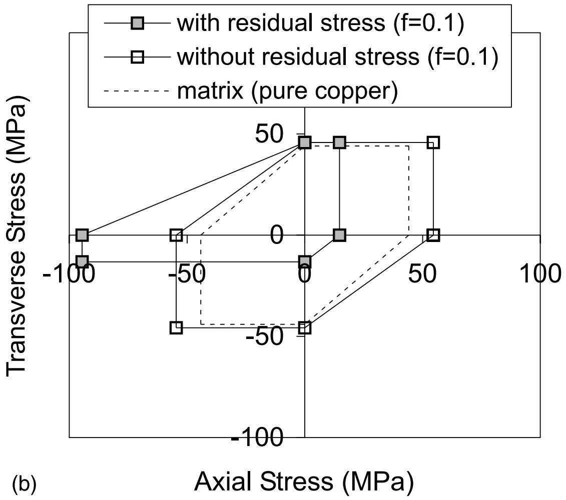
Table 1
Properties of the matrix and the fiber materials at room temperature [9,10]

	Copper	CuCrZr	SiC fiber
Young modulus (GPa)	130	128	430
Poisson ratio	0.34	0.3	0.17
Yield stress (MPa)	44	300	–
Work-hardening rate (MPa)	1550	1050	–
Thermal conductivity (W/m K)	400	380	16
CTE[a] (10^{-6}/K)	16.7	15.7	5.7

[a] Coefficient of linear thermal expansion.



(a)

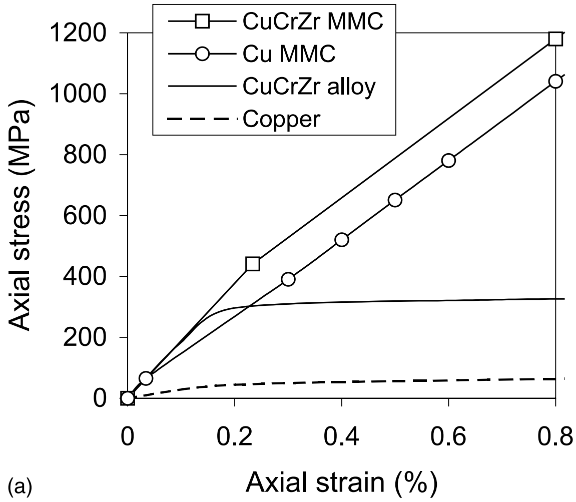


(b)

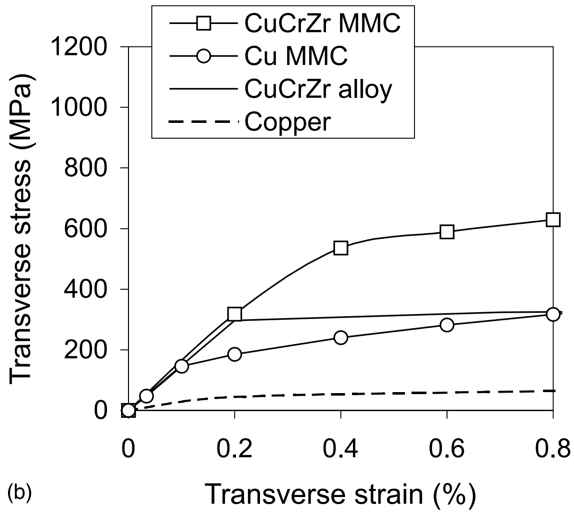
Fig. 1. Effective global initial yield surfaces of two FRCMCs for $f = 0.1$ in bi-axial principal stress spaces each with matrix of CuCrZr alloy (a), and with pure copper (b), respectively. (Abscissa denotes the stress in fiber axis direction whereas ordinate the stress in transverse direction.)

For each composite, two different states are compared: with and without thermal residual stresses. To consider the thermal residual stresses, the so-called effective temperature change of cooling, ΔT_{eff}, is introduced, which takes also the relaxation during cooling into account. In this study, −100 °C is taken for ΔT_{eff}, since it is a typical value for fiber-reinforced metal matrix composites [9]. The general pattern is that the existence of the thermal residual stress field leads to the shape change of the elastic domain as well as the translation to second quarter plane. The elastic domain in the other quarter planes is reduced. In particular, the composite with pure copper matrix experiences a more pronounced change due to its small flow stress. To interpret this behavior, it should be noted that the yield loci were determined considering three-dimensional stress states, though they are plotted in the two-dimensional stress space. Hence, either a larger effective temperature change of cooling ΔT_{eff} or higher fiber reinforcement will lead to a decrease of the yield strength in axial tension or transverse compression and to an increase of the yield strength in axial compression. The yield strength in transverse tension is just slightly affected.

In Fig. 2, the simulated effective global stress–strain curves for the total global strain of up to 2% is shown. The most salient feature is that both composites show



(a)



(b)

Fig. 2. Simulated effective global stress–strain curves each for axial loading (a) and transverse loading (b) cases, respectively. Curves for FRCMCs with either CuCrZr alloy matrix or pure copper matrix are shown. ($f = 0.2$, $\Delta T_{\mathrm{eff}} = -100$ °C) The square mark denotes tensile load and the triangle denotes compressive load.

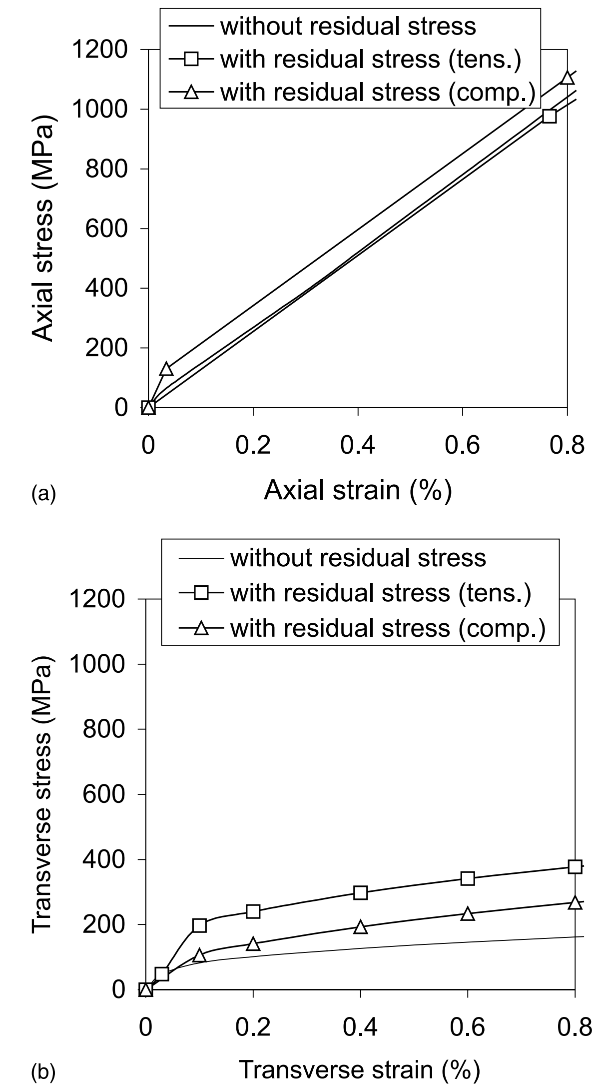


Fig. 3. Effect of the thermal residual stresses on the global stress–strain curves (a) for axial loading, (b) for transverse loading. Curves are for the FRCMC with pure copper matrix. ($f = 0.2$, $\Delta T_{\mathrm{eff}} = -100$ °C) The square mark denotes tensile load and the triangle denotes compressive load.

fairly strong effective work-hardening rate in the plastic range under axial loading. In case of transverse loading, the work-hardening rate is less pronounced than in the axial loading case but still higher than that of the matrix materials. The effective work-hardening rates of the two FRCMCs are similar to each other, though CuCrZr and pure copper have a quite different work-hardening rate. This can be elucidated considering the relation for the effective work hardening [9]

$$\frac{\partial \sigma_{\mathrm{a}}}{\partial \varepsilon_{\mathrm{pl}}^{\mathrm{c}}} = \frac{W}{P} + \frac{1}{P(1-f)} \frac{\partial \sigma_{y}^{(\mathrm{m})}}{\partial \varepsilon_{\mathrm{pl}}^{(\mathrm{m})}}. \tag{9}$$

W/P depends on the reinforcement system (form and volume fraction) and loading condition whereas the second term on the right side stands for the contribution from the matrix work-hardening rate. In the present case, W/P term prevails and the influence of the matrix work-hardening rate is shielded.

In Fig. 3, the global stress–strain curves for the FRCMC with pure copper matrix are plotted again to show the effect of the thermal residual stresses. For comparison, the global stress–strain curves for the same composite which is free of residual stresses are plotted also. It is seen that the residual stresses affect the global yielding in different manner depending on the specific loading direction. From the results given above, it can be concluded that the thermal residual stress should be reduced in case that axial loading dominates, since it causes a decrease of global yield strength under tension. The asymmetry in tension and compression is due to the thermal residual stresses. This can be understood by noting that tensile stress develops in the matrix during the cooling process, since the metallic matrix undergoes much larger differential thermal contraction than the ceramic fibers.

It should be noticed that the mean field premise causes an overestimation of flow stress, since local yielding due to stress fluctuation cannot be considered. Further, it is difficult to obtain the in situ yield stress of the composite matrix after processing. The thermo-mechanical treatment during composite processing will certainly cause a significant metallurgical evolution of the matrix.

4. Summary

The FRCMCs can be a potential candidate as a structural material for the heat sink of the actively cooled plasma facing components, since they can have various beneficial properties resulting from the combination of properties of the constituent materials. In this article, the non-linear constitutive behavior of the FRCMCs reinforced with continuous SiC fibers was predicted using mean field micro-mechanics theory. The FRCMCs showed significantly increased work-hardening rate in comparison to the unreinforced matrix metals. This may be the most interesting feature for structural applications. The thermal residual stress has a marked influence on the initial yield surface as well as on the stress–strain curves. Under the thermal residual stresses, the tensile global yield stress for axial loading decreased whereas the opposite effect occurred under compression. It might be necessary to apply a layered stacking concept to maximize the effect of reinforcement by utilizing the axial loading of individual lamina. The analytical mean field model provided a straightforward prediction for the plastic deformation of the FRCMCs.

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