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Overall mechanical properties of fiber-reinforced metal matrix composites for fusion applications

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Abstract

The high-temperature strength and creep properties are among the crucial criteria for the structural materials of plasma facing components (PFC) of fusion reactors, as they will be subjected to severe thermal stresses. The fiber-reinforced metal matrix composites are a potential heat sink material for the PFC application, since the combination of different material properties can lead to versatile performances. In this article, the overall mechanical properties of two model composites based on theoretical predictions are presented. The matrix materials considered were a precipitation hardened CuCrZr alloy and reduced activation martensitic steel 'Eurofer'. Continuous SiC fibers were used for the reinforcement. The results demonstrate that yield stress, ultimate tensile strength, work hardening rate and creep resistance could be extensively improved by the fiber reinforcement up to fiber content of 40 vol.%. The influence of the residual stresses on the plastic behavior of the composites is also discussed.

1. Introduction

Structural materials of plasma facing components (PFCs) for future fusion reactors should withstand high heat flux (HHF) loads and energetic neutron irradiation. The ability to remove incident stationary heat fluxes of 10–20 MW/m^2 is the prime objective for the divertor component whereas reduced activation and mechanical stability under irradiation and high operation temperatures are the important concerns for the PFCs in general [1,2]. It is obvious that the mechanical strength at elevated temperatures is one of the crucial criteria for the structural materials, as the PFCs will be subjected to considerable thermal stresses.

As divertor heat sink material until now both the dispersion strengthened (DS) and the precipitation hardened (PH) Cu-alloys have been investigated to suppress the loss of strength at elevated temperatures [1,3–5]. According to the estimation in [6] based on the RCC-MR code, the PH copper alloys could be used for the PFCs up to 350 °C under the applied stress intensity of 100 MPa (however, PH Cu is not code qualified yet). On the other hand, the large coefficient of thermal expansion (CTE) of these alloys is detrimental to the strength of a joint component consisting of two or three materials bonded each other.

For the first wall and blanket structures of future reactors, the so called reduced activation martensitic steels (RAMS) have been intensively developed in the last decade [2,7]. The service temperature of such steels like Eurofer is normally limited to 550 °C. Recently, there has been a research effort to develop the oxide dispersion strengthened (ODS) RAMS to improve the high-temperature strength [8]. It is expected that an increase of the service temperature by more than 100 °C can be achieved with the ODS RAMS compared to the plain RAMS. The higher service temperature of the first wall and blanket components will lead to an increased energy efficiency of a fusion power plant.

Compared to these candidate materials the fiber-reinforced metal matrix composites (FRMMCs) could

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become potential candidate materials for the PFC application, since the combination of different properties of fiber and matrix can lead to versatile performances of these materials [9]. They can possess much higher ultimate strength, work hardening rate and creep resistance than the conventional PH or ODS alloys in a wide temperature range. The global yielding is usually increased by the fiber reinforcement. But the yield stress of a FRMMC can be influenced by residual stresses. The ultimate load carrying capacity of such composites will depend either on the onset of unconstrained plastic flow of the matrix or on the overall fiber fracture. The elastic stiffness as well as the thermal expansion coefficient can be tailored to some extent. This feature may be advantageous for a bond joint PFC, which consists of the plasma-facing material being bonded to the heat sink, since the thermal mismatch stresses resulting from this material joining can be reduced. Permanent dimensional change by plastic ratcheting can be effectively suppressed. In addition, the FRMMC can be introduced locally into the highly loaded regions of the PFCs.

An example of the engineering applications of the FRMMCs, although not introduced into the commercial production yet, is an engine component of an aircraft called blings, a compound of turbine blades and a rotor ring, which will be exposed to a similar HHF environment [10].

In this article, the overall thermo-mechanical properties of two different model FRMMCs are presented. The whole results given here are based on theoretical investigation. For brevity, the details of the theoretical background, with which the predictions of composite behavior are made, will not be presented.

2. Materials and microstructure

As matrix materials, the two aforementioned metals are used: a PH copper alloy, CuCrZr, and a RAMS, Eurofer 97 (9CrWVTa). For the reinforcement, continuous SiC fibers are used. The properties of these materials are listed in Table 1. Only the case of a unidirectional fiber array is treated and perfect interface is assumed. It is further assumed that firstly, the mechanical properties of the matrix materials do not change through the composite processing and that secondly, there exists no residual stress. These premises may not be valid in certain practical cases.

Table 1
Properties of the matrix and the fiber materials at RT [7,11,12,14]

	CuCrZr	Eurofer	SiC long fiber
Young's modulus (GPa)	128	206	430
Poisson's ratio	0.34	0.3	0.17
Coefficient of linear thermal expansion (10^{-6} K^{-1})	15.7	10	5.7
Yield stress (MPa)	297	570	
Work hardening rate (MPa)	1050	≅2500[a]	
Ultimate tensile strength (MPa)	413	670	3800

[a] Data of RAMS F82H from [13].

3. Thermo-elastic properties

In Fig. 1, the elastic moduli of the model FRMMCs at room temperature (RT) are plotted for various fiber volume fractions. The results were obtained using the Mori–Tanaka mean field theory based on the Eshelby theory (here called Eshelby method) [15,16]. According to this theory, the elastic stiffness tensor of a FRMMC is given by [14]

$$E^c = \{E_l^{m-1} - f\{(E^f - E^m)[S - f(S - I)] - E^m\}^{-1} \times (E^f - E^m)E^{m-1}\}^{-1},$$

where S denotes the Eshelby tensor, I is the fourth rank identity tensor, f is the fiber volume fraction and $E^{()}$ stands for the elastic stiffness matrix. The superscript c, m and f means composite, matrix and fiber, respectively.

It is seen that the moduli in axial direction follow the Voigt rule while the transverse moduli show a Reuss type behavior. For comparison, the transverse modulus of the CuCrZr FRMMC calculated by two other micromechanics methods (Hill's method [17] and Hashin's method [18]) are plotted in Fig. 1, too. The Eshelby method shows a good agreement with the other fully analytical results.

In Fig. 2, the coefficients of thermal expansion (CTEs) of the two FRMMCs are plotted. These CTE

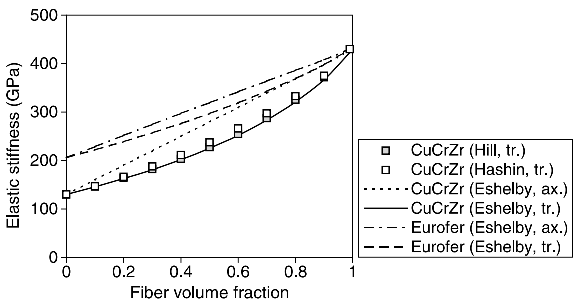

Fig. 1. Elastic moduli of the model FRMMCs at RT plotted for various fiber contents. For the CuCrZr FRMMC, the result obtained using the Mori–Tanaka mean field theory (labeled as Eshelby) is compared with the predictions by two other micromechanics models (labeled as Hill and Hashin).

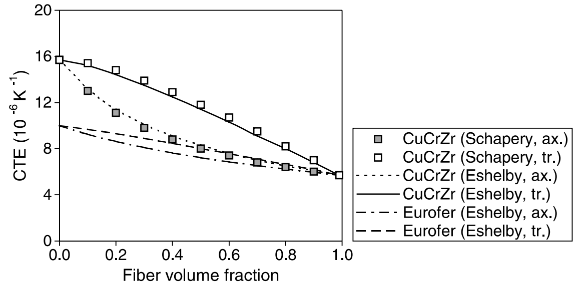

Fig. 2. Coefficients of thermal expansion of the two FRMMCs at RT plotted for various fiber contents. For the CuCrZr FRMMC, the result obtained using the Mori–Tanaka mean field theory (labeled as Eshelby) is compared with the prediction by the Schapery models.

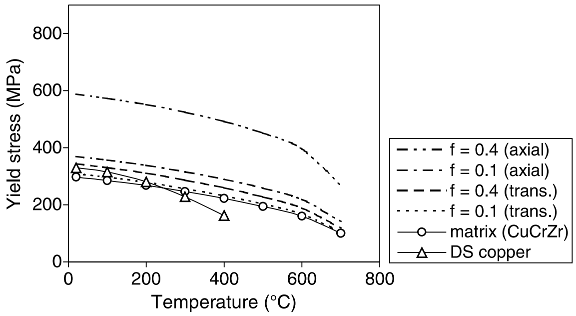

Fig. 3. Global yield stresses of the CuCrZr FRMMC for two different fiber volume fractions f (10 and 40 vol.%). For comparison, the experimental data of the ODS alloy as well as of the matrix alloy are also given.

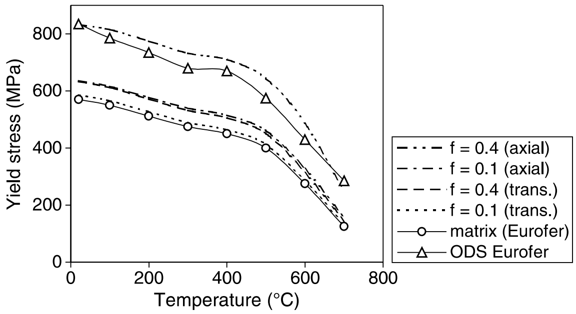

Fig. 4. Global yield stresses of the Eurofer FRMMC. For comparison, the experimental data of Eurofer and ODS-Eurofer are also given.

values were obtained using the following formula derived from the Mori–Tanaka mean field theory [14],

$$\alpha^{c} = \alpha^{m} - f\{(E^{m} - E^{f})[S - f(S - I)] - E^{m}\}^{-1}E^{f}(\alpha^{f} - \alpha^{m}),$$

where α denotes the CTEs. The superscripts have the same meaning as before.

The CTEs of the CuCrZr FRMMC obtained by the Eshelby method are compared with those of the Schapery model [19]. They show a good agreement in both directions as well. The dependence of the CTEs in the axial direction on the fiber volume fraction deviates from the rule of mixture. It is clear that the SiC fiber reinforcement will lead to a salient reduction of thermal stresses in a joint PFC furnished with a copper heat sink, since plasma facing materials usually have a much smaller CTE than copper alloys.

4. Plastic properties

4.1. Global yield stress

The global yield stresses (in the following, yield stresses) of the CuCrZr and the Eurofer FRMMC are plotted in Figs. 3 and 4, respectively. The results are presented for two different fiber volume fractions and for a temperature range up to 700 °C. Most of the practical cases will be covered by these parameter windows.

The theoretical method to obtain the yield stresses was the elasto-plastic Mori–Tanaka type mean field theory based on the Eshelby theory suggested by Withers et al. [20]. In this model, it is assumed that the global yielding of a FRMMC is governed only by the plastic flow in the matrix. In the framework of the mean field scheme, the onset of global yielding of the FRMMC is determined by investigating whether the phase averaged total stress state in the matrix satisfies the Tresca yield condition which would give rise to flow if it were experienced by the matrix material free from the reinforcement. It was demonstrated elsewhere that this method allows one to determine the yield surface of a copper FRMMC which was relatively in good agreement with the finite element analysis [21].

The results of both FRMMCs indicate that the yield stresses in the axial direction can be effectively increased by the fiber reinforcement whereas the effect is much weaker in the transverse direction. This is a natural consequence of the load transfer and the constraint of neighboring fibers both of which are maximized in the axial direction. The axial yield stresses of both FRMMCs are significantly increased by a fiber reinforcement of 40 volume percents (vol.%). The trend of the temperature dependence remains unchanged either by the fiber concentration or by the loading direction.

An important feature revealed by the comparison with the measured results for the (O)DS alloys is that the yield stress of the Eurofer can be as effectively improved by the ODS technique as the fiber reinforcement whereas the yield stress of the ODS copper is essentially lower than that of the FRMMC with PH copper alloy matrix

[8,11]. It is remarkable that the ODS Eurofer has yield stress values which are comparable to those of the FRMMC with 40 vol.%. In contrast to this, the ODS copper has just similar yield stress values to the matrix alloy CuCrZr, though a notable strengthening of copper was achieved through the ODS technique.

4.2. Work hardening rate

One of the most dominant effects of the fiber reinforcement is the strong work hardening rate after initial yielding. Fig. 5 shows the constitutive relations of the CuCrZr FRMMC in the plastic region for two different fiber volume fractions and loading directions. These results were obtained using the incremental elasto-plastic Mori–Tanaka type mean field theory based on the Eshelby theory as formulated by Benveniste [22] and Pettermann [23]. In this model, the von-Mises yield condition and the Prandtl–Reuss flow rule was used. It was shown that this method yielded stress–strain curves of a copper FRMMC which are in excellent agreement with the finite element analysis for the axial loading case whereas the predictions for the transverse loading case were somewhat overestimated [21].

The characteristic strong work hardening is also found here especially in the axial direction and in the range of higher fiber vol.%. This can be better appreciated by comparing the composite curves with those of the matrix alloy. The same trend will be obtained for the Eurofer FRMMC, since the increase of the work hardening rate through the fiber reinforcement is so large that the inherent work hardening rate of the matrix alloy can hardly impose an influence on it.

4.3. Ultimate tensile strength

It is natural to expect that the extreme high fracture strength of ceramic fibers will contribute to a considerable increase of the ultimate tensile strength (UTS) of FRMMCs. In order to utilize this advantage for the design of structures, one should notice that the strengthening effect depends strongly on the loading direction as well as on the fiber volume fraction. In addition, the bonding strength at the fiber–matrix interfaces is another important parameter.

In Figs. 6 and 7, the UTS values of the two FRMMCs in the axial as well as in the transverse direction are plotted. As in the previous plots, they are given for two different fiber volume fractions and for a temperature range up to 700 °C. The theoretical models used for the prediction were the modified rule of mixture for the axial UTS [14,24] and the cylindrical hole model by Clyne et al. for the transverse UTS [14]. It was reported in several experimental studies that the modified rule of mixture could describe the axial UTS of various FRMMCs up to ≈40 vol.% fairly well [25,26]. In the cylindrical hole model, the fibers are treated as if they were a set of cylindrical holes. This is of course not a realistic model, since the stress state in the matrix will be affected by the presence of the stiff fibers even though

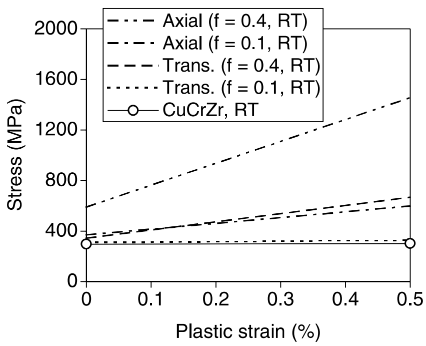

Fig. 5. Constitutive relations of the CuCrZr FRMMC in the plastic regime for two different fiber volume fractions f and loading directions.

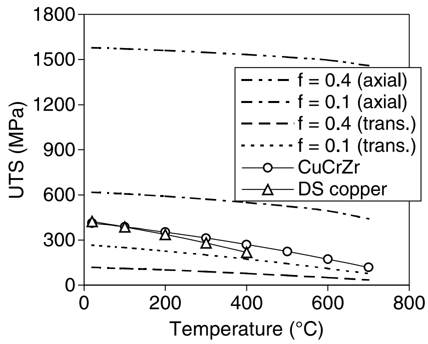

Fig. 6. Ultimate tensile strength of the CuCrZr FRMMC in the axial as well as in the transverse direction plotted for two different fiber volume fractions f.

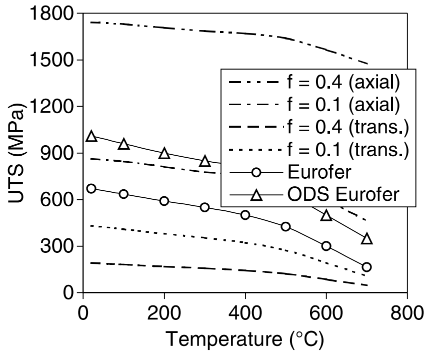

Fig. 7. Ultimate tensile strength of the Eurofer FRMMC. For comparison, the experimental data of Eurofer and ODS-Eurofer are also given.

they are completely debonded. It was shown experimentally that this model can be a useful guide for a FRMMC which has either a weak interfacial bonding or fibers with low fracture strength [27]. Thus, the current predictions of the transverse UTS should be interpreted as giving the lower bounds of the UTS in a conservative estimation. The upper bounds, which correspond to the case of a perfect interface, will be the curves of the matrix materials.

It is notable that the UTS of the FRMMCs can be effectively improved by increasing the fiber content. The DS copper has similar UTS values as the PH copper CuCrZr while the UTS of the ODS Eurofer lies in the similar level compared to that of the FRMMC with 10 fiber vol.%. To make more realistic predictions, a statistical treatment is required, since the fracture of the fibers cannot be described in a deterministic manner.

4.4. *Effect of thermal residual stress*

There have been experimental evidences that the macroscopic plastic behavior of a FRMMC can be influenced by thermal residual stresses [28]. The most prominent effect may be the asymmetry of the yield stress between tension and compression [20]. This effect is found in the whole flow process showing a splitting of the stress–strain curve and its magnitude depends undoubtedly on the magnitude of the thermal residual stresses. This phenomenon was explained also by numerical simulations [29,30].

Since the intensity of the thermal residual stresses is determined by various process parameters as well as by the in situ flow stress of the matrix, the evaluation demands a careful approach. A few analytical models have been proposed based on diverse theoretical considerations [28,29].

In Fig. 8, the initial yield surfaces of the CuCrZr FRMMC are illustrated on a bi-axial projection plane of the stress space. The abscissa denotes the stress component parallel to the fiber orientation while the ordinate stands for the stress component being perpendicular to it. This result was obtained using the modified Pedersen's Mori–Tanaka type mean field theory considering the plastic yield during cooling process [20]. Three yield surfaces of the FRMMC are plotted. The contour line without marking indicates the yield surface of the fiber-free matrix while the contour lines marked with closed circles and open circles denote the yield surfaces of the composite each with and without residual stresses, respectively. To include the effect of the residual stresses, it was assumed that the temperature drop during the cooling process was 100 °C.

The diagram shows clearly that the yield surface is shifted in the direction of the axial compression under the presence of residual stresses. This can be understood considering the fact that tensile stress develops in the

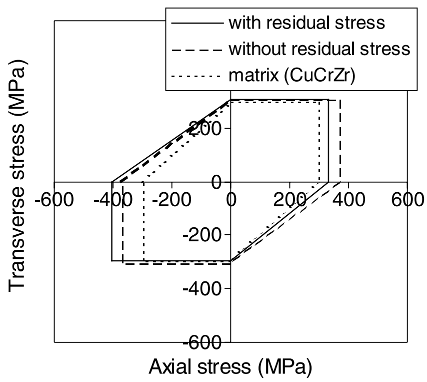

Fig. 8. Initial yield surfaces of the CuCrZr FRMMC illustrated on a bi-axial projection plane of the stress space. The abscissa denotes the stress component parallel to the fiber orientation while the ordinate stands for the component being perpendicular to it. To include the effect of the residual stresses, it was assumed that the temperature drop during the cooling process was 100 °C.

matrix during the cooling process, since the metallic matrix undergoes much larger differential thermal contraction than the ceramic fibers. The present analysis indicates that the fiber reinforcement may not necessarily result in an improvement of the tensile yield stress especially when the matrix alloy has a high CTE or the processing temperature is high.

The effect of the residual stresses on the matrix yield implies that they should also have an effect on the UTS of a FRMMC. However, it will be by no means very pronounced, since the large fracture strength of the fibers will dominate against the change of the matrix stress for materials with higher fiber content while the effect the residual stresses will not be dominant for those with lower fiber content.

5. Creep resistance

It is well known that most ceramic fibers possess a much stronger creep resistance than alloys up to 800 °C [12]. For axial loading, the long term creep rupture life of a FRMMC will be determined actually by the creep rupture of the fibers. In case of the transverse loading, the creep rate of a FRMMC will not differ essentially from that of the matrix materials.

In Fig. 9, the creep curves of the two FRMMCs are plotted for two different fiber volume fractions. The applied stress was 200 MPa. Two different temperatures were applied to the composites: 600 °C for Eurofer FRMMC and 400 °C for CuCrZr FRMMC. These creep curves were calculated using the asymptotic fitting model given by Clyne et al. [14]. This model assumes that a steady state of creep is established under axial

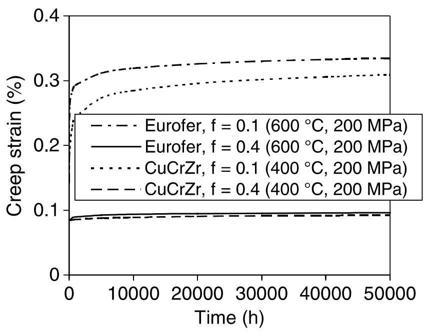

Fig. 9. Creep curves of the two FRMMCs plotted for two different fiber volume fractions. The applied stress was 200 MPa. Two different temperatures were applied to the composites: 600 °C for Eurofer FRMMC and 400 °C for CuCrZr FRMMC.

loading in which the continuous fibers bear all the load. The composite creep rate will depend on the creep behavior of the fiber. In the temperature range where creep of the fiber remains still minute, the creep strain of a FRMMC will approach asymptotically the maximum strain which is determined by the elastic modulus of the fiber and the fiber volume fraction.

The results show that the creep deformation in the axial direction is significantly suppressed by the fiber reinforcement, so that for 40 fiber vol.% it can be actually neglected under the normal PFC operation condition. Even for 10 fiber vol.%, the creep strain does not exceed 0.4% after 50 000 h in both FRMMCs. It is expected that the saturated creep strain will change inverse proportionally to the elastic modulus of the fiber while being rather insensitive to temperature up to 800 °C. The creep strains in the transient phase were calculated using the data of creep rupture (i.e. the Larson–Miller master curves) and maximum uniform elongation for the matrix materials [7]. Hence the present curves would be a conservative estimation, which, however, will not make a notable difference.

6. Conclusions

Theoretical predictions on several key mechanical behaviors of two selected FRMMCs, each with the matrix of CuCrZr alloy and Eurofer steel, were performed. Unidirectional reinforcement of continuous SiC fibers was assumed. Since these matrix materials have been considered as the structural materials for the PFCs, attention was paid to the question how much the fiber-reinforced composites can enhance the performance of the matrix alloys at elevated temperatures.

The results suggested that these composites can be an attractive candidate for the PFCs of future fusion devices, especially in view of their extended high temperature strength and creep resistance. It was demonstrated that the overall mechanical properties of the matrix metals such as the yield stress, the ultimate tensile strength, the work hardening rate and the creep resistance could be significantly improved through the reinforcement of long SiC fibers up to 40 vol.%.

In fact, this statement is valid only for the axial properties since the reinforcement effect for the transverse direction was weak. To fully exploit the merits of the fiber reinforcement, it may be needed to apply composites with reinforcement in the form of a laminated multilayer. The comparison with the experimental data of the ODS variants of the matrix materials showed that the fiber composite of the PH copper had properties superior to those of DS copper. For the case of the Eurofer-matrix fiber composite, the ODS Eurofer had comparable strength properties, but a much lower creep resistance.

It was also demonstrated that the thermal residual stresses have an influence on the plastic flow in the matrix. This feature should be taken into account for more accurate evaluation of the composite strength.

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