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Numerical study on the creep behavior of the metal matrix short fiber composites with application in optoelectronic and photonic devices

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FEM study is carried out for predicting the behavior of the short fiber composites in the steady state creep with application in optoelectronic and photonic devices. The study on the creep behavior is necessary in order for failure, fracture, fatigue, and creep resistance of the short fiber composites. In this article, the creep behavior of the short fiber composite is predicted under tensile axial loading by the numerical method. One of the significant applications of the work is in the short fiber composite designing and optimizing. Also, the available experimental results [10] are used for the FEM simulation.

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1. Introduction

The use of the photonic fibrous composites is newly growing owing to their applications in different industries. Creep in the systems may make the serious disturbances in the advanced photonic systems. Recently, analysis of the steady state creep behavior of the short fiber composites has become an important subject and topic in the scientific societies because these materials have a high potential for use in structural applications at the elevated temperatures and applied stresses. Increasing number of applications of the short fiber composites makes these materials more significant to understand and predict their creep characteristics and deformation mechanisms. It is well known that the short fiber composites present considerably better creep resistance than the related non-reinforced materials.

Consequently, an exact FEM study on the creep behavior and its mechanisms for the reinforced materials is significant and crucial, because, the occurrence of the creep in the fibrous composites such as electrical and optoelectronic/photonic devices can be very dangerous. So the creep study becomes more important in the different industries. Many researchers have investigated the steady state creep behavior by analytical and experimental methods. The experimental and analytical methods are generally difficult and complex, and sometimes impossible for predicting the composite creep behavior exactly. So, because of the several difficulties of the experimental and analytical methods, the present FEM study is proposed for predicting these behaviors in place of the experimental and analytical methods. Newly, the extensive studies were done to predict the steady state creep behavior of the short fiber composites by various analytical and experimental methods.

Interesting researches were done about the steady state creep analysis of the fibrous composites. In which, theoretical methods basically include the shear-lag models (Cox, 1952; Nairn, 1997), imaginary fiber technique (Jiang et al., 2005; Monfared et al., 2015), and different mathematical methods (Zhang, 2003; Spathis and Kontou, 2012; Hamed and Chang, 2013; Zhao et al., 2015; Monfared et al., 2015). An important model known as shear lag model has been one-dimensionally proposed to analyze stress transfer in unidirectional long or short fiber composites (Cox, 1952). Also, the other different mathematical methods were employed for analyzing the steady state creep of the short fiber composites such as methods based on parametric study based on shear model (Zhang, 2003), thermally activated rate process (accounting the viscoelastic path at small strains and the viscoplastic path at higher stresses) (Spathis and Kontou, 2012), layered structure and rheological generalized Maxwell models (Hamed and Chang, 2013), dislocation climb model (Zhao et al., 2015). Moreover, the effect of the creep on the edge debonding failures of FRP strengthened beams was studied analytically and experimentally (Hamed and Chang, 2013). They have shown that the creep of the concrete and the adhesive lead to a redistribution of the interfacial edge stresses, which can magnify or diminish the ultimate load that leads to edge debonding failures. Also, effect of atomic number and atomic weight on time-dependent inelastic deformation at metals was studied by Monfared et al. (2015).

Numerical methods have been done for analyzing the creep in the short fiber composites (Dragon and Nix, 1990; Ismar et al., 2000; Kim et al., 2008). For example, the creep potential and its numerical formulation were carried out using finite element method (Kim et al., 2008), in which, it was shown that the creep model based on "an equation of state" method can be used to efficiently design moderate span enclosures.

Also, some researchers have experimentally attempted to predict the creep behavior of the materials (Morimoto et al., 1988; Yang and Yu, 2013; Glaskova-Kuzmina et al., 2014; Guo et al., 2014; Yang et al., 2015; Aslani, 2015). The effect of carbon nanotubes (CNTs) has been studied on the elastic and viscoelastic properties of an epoxy resin used in carbon fiber-reinforced plastics (CFRPs) in the matrix-dominated flexural testing mode (Glaskova-Kuzmina et al., 2014). A series of fire-resistant steel columns with 3 various slenderness ratios under a sustained load were tested under a uniform temperature up to six hours in order for evaluating the creep upon 3 chosen factors, temperature, applied load, and column slenderness (Yang and Yu, 2013). Aslani (2015) studied and reviewed the accuracy of the conventional concrete (CC) creep prediction models proposed by the international codes of practice.

As a different and interesting research work, the performance of woven Sylramic-iBN fiber-reinforced slurry cast melt-infiltrated (MI) composites have been tested in the creep and fatigue under non-oxidizing conditions in order for better understanding the effect of stressed-oxidation (Morscher et al., 2011).

In present research work, a comprehensive FEM study is done to predict and analyze the creep behavior of the short fiber composite in the second stage creep using the micro-creep model of the optoelectronic/photonic composites numerically. A FE model is presented for prediction of the steady state creep behavior of the short fiber composites instead of the difficult and time-consuming experimental and analytical methods. The experimental results of a metal matrix composite (*SiC/Al6061*) are selected to predict the creep behavior of it.

2. Material and method

Here, an axisymmetric unit cell is assumed as a representative of the full short fiber composite with a fiber with its surrounding matrix as two coaxial cylinders. The model of the unit cell model is schematically shown in Fig. 1. Moreover, a complete fiber-matrix interface is assumed.

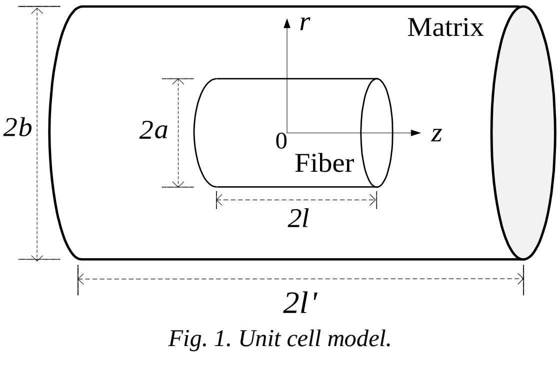

Fig. 1. Unit cell model.

In the present model, it is assumed that a cylindrical fiber with a radius a and a length $2l$ is inserted in a coaxial cylindrical matrix with an outer radius b and a length $2l'$. The volume fraction and aspect ratio of the fiber are introduced by f and $s=l/a$ respectively. As well, $k = l'a/lb$ is considered as a parameter in relation with the geometry of the unit cell. An applied axial tensile loading "σ_0", is uniformly applied on the end faces of the unit cell (at $z=\pm l'$). The creep behavior of the matrix is described by an exponential law as the following in Eq. (1),

$$\dot{\varepsilon}_{equivalent} = A\,exp\left(\frac{\sigma_{equivalent}}{B}\right) \tag{1}$$

Where A and B are the steady state creep constants of the creeping matrix material and the equivalent stress $\sigma_{equivalent}$ and the equivalent strain rate $\dot{\varepsilon}_{equivalent}$ are given by following,

$$\sigma_{equivalent} = \frac{\sqrt{2}}{2}\sqrt{\left(\sigma_{rr}-\sigma_{\theta\theta}\right)^2+\left(\sigma_{\theta\theta}-\sigma_{zz}\right)^2+\left(\sigma_{zz}-\sigma_{rr}\right)^2+6\tau_{rz}{}^2} \tag{2}$$

$$\dot{\varepsilon}_{equivalent} = \frac{\sqrt{2}}{3}\sqrt{\left(\dot{\varepsilon}_{rr}-\dot{\varepsilon}_{\theta\theta}\right)^2+\left(\dot{\varepsilon}_{\theta\theta}-\dot{\varepsilon}_{zz}\right)^2+\left(\dot{\varepsilon}_{zz}-\dot{\varepsilon}_{rr}\right)^2+6\dot{\varepsilon}_{rz}^2} \tag{3}$$

Where the parameters, "$\dot{\varepsilon}_{rr},\dot{\varepsilon}_{\theta\theta},\dot{\varepsilon}_{zz}$", and "$\dot{\varepsilon}_{rz}$" are the strain rate components in the directions indicated by subscripts. Also, the parameters, "σ_{rr}, $\sigma_{\theta\theta}$, σ_{zz}", and "τ_{rz}" are the radial, circumferential, axial, and shear stress components, respectively. The FEM is presented for predicting the composite creep behavior in the next section.

One of the advantages of the FEM model is in exact and simple modeling of the creeping unit cell instead of the time consuming and difficult analytical and experimental methods. Additionally, the analysis helping FEM model is very easy for obtaining the composite creep behavior. General representation of the finite element model with its appropriate boundary conditions and coupling conditions under tensile axial loading is shown in Fig. 2. The numerical computations of the steady state creep behavior are done using the FEM commercial code of ANSYS.

To predict the creep behavior, the finite element numerical calculations of steady state creep behavior of the fibrous composite are also done using the finite element commercial code of ANSYS (version 13.0). The axisymmetric unit cell model is assumed for FEM creep analysis. The axisymmetry approach with nonlinear quadratic element of plane 185 is used for FEM prediction and modeling. This element is a higher order eight-node element and has creep modeling capability appropriately.

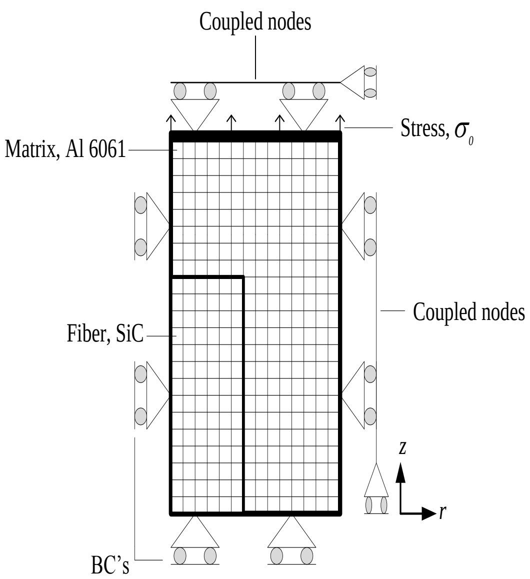

Fig. 2. General and axisymmetric model of the unit cell for FEM creep analyzing.

3. Result and discussion

For analysis of creep behavior of the short fiber composite by the FEM, the $SiC_{fiber} / Al_{matrix}$ composite is chosen as a case study. For the composite used here SiC_f / Al_m, the volume fraction of fibers is *0.15* and the fibers have an aspect ratio of *7.4* and $k = 0.76$, which are according to the suggestions made in [10]. In addition, for the creeping the matrix, the constants are the values of $A = exp(-24.7)$ and $B = 6.47$ considering "$\sigma_0 = 80\,MPa$" at 573 *K*. In the present research, the purpose of the creep analysis is in the suitable composite design. That is, the creep behavior must be analyzed to prevent the failure and defect in the creeping short fiber composites.

The results obtained from the present FEM are presented in Figs. 3-6.

Based on the predicted behaviors, we can control the composite creep behavior because of the smooth and uniform gradients (see Figs. 3, 4). The finite element (FEM) analysis of the creep behavior is schematically shown in Figs. 3-6. The FEM analysis and solution may be useful for better designing the short fiber composite devices. For example, the general trend and behavior of the axial stress at the interface ($r=a=1$) is descending (see Fig. 3).

To compare the results of the present method, the SiC/6061Al composite is selected as a case study and also the determined analytical and numerical results are compared with together because of lack of the experimental data of the creeping optoelectronic and photonic composites.

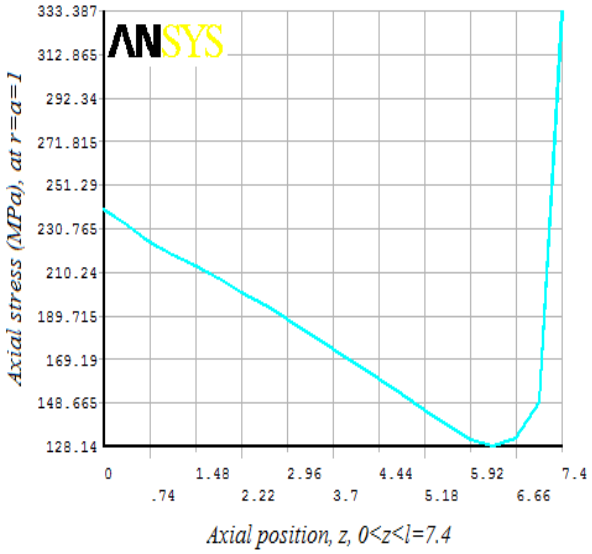

Fig. 3. The behavior of the axial stress at the interface (at $r=a=1, 0<z<l=7.4$, $\sigma_0 = 80\,MPa$)

In addition, the general trend and behavior of the radial stress at the interface ($r=a=1$) is ascending (see Fig. 4). With considering these ascending and descending behaviors, we can control the creep behavior of the short fiber composites. Also, the uniform and smooth gradients are seen in the axial and radial stress curves and values (see Figs. 3, 4).

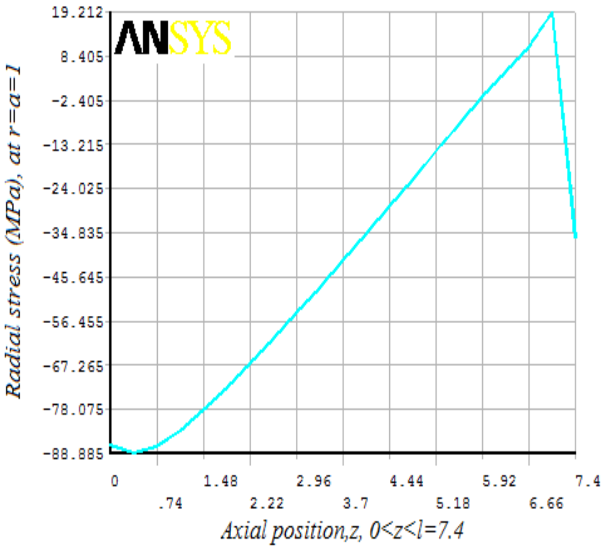

Fig. 4. The behavior of the radial stress at the interface (at $r=a=1, 0<z<l=7.4$, $\sigma_0 = 80\,MPa$)

Fig. 5 presents graphically the complete distribution of the creep radial stress (in the *r*-direction) using the contour nodal solution data in the unit cell. This distribution can be beneficial for better designing the fibrous composites.

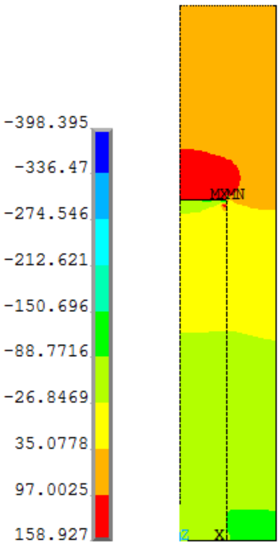

Fig. 5. Contour nodal solution data for radial stress (in the r-direction) in the creeping unit cell

Also, Fig. 5 presents the dangerous and weak regions for the creeping short fiber composite numerically and schematically. Moreover, Fig. 5 (distribution of the radial stress in the unit cell) can help us for preventing from debonding and creep rupture in the short fiber composites. In addition, the nodal solution of the creep strain energy density for a unit cell is graphically shown in Fig. 6 (distribution of the creep strain energy density). This contour nodal solution may help to engineers for better designing the short fiber composites.

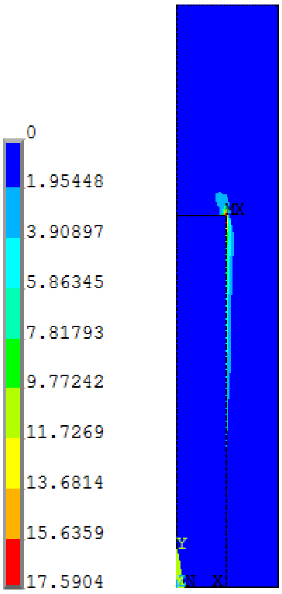

Fig. 6. Contour nodal solution results for the creep strain energy density in the creeping unit cell

Figs 5 and 6 show that the regions nearing top of the fiber end are critical and important, because the debonding and creep rupture may happen in these regions. That is, the maximum values are seen on the top of the fiber end in Figs. 5 and 6.

4. Summary and conclusion

In this work, FEM study was done for predicting the behavior of the short fiber composites in the steady state creep with application in optoelectronic and photonic composite devices. In this article, the short fiber composite creep behavior was predicted under tensile axial loading by the numerical method. One of the significant applications of the work is in the short fiber composite designing and optimizing. Also, the experimental results were used for the FEM simulation. Distribution of the radial stress (contour nodal solution) and distribution of the creep strain energy density in the unit cell may help to engineers to prevent the debonding and creep rupture in the short fiber composites.

One of the advantages of the present model is in the application of the FEM instead of time consuming and complex experimental and analytical methods. Finally, we can rely on the FEM results for predicting the creep behavior in the short fiber composites. In addition, the ascending and descending behaviors were seen in the radial and axial stress behaviors respectively. However, the uniform gradients were considered for these stress values. Thus, we can control the composite creep behavior due to these smooth gradients. So, the numerically predicting the creep behavior of the short fiber composites is very significant for better designing the fibrous composites in the steady state creep of these composites.

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