Practical Applicability and Limitation of Representative Volume Element Approach to Model Creep Behaviors of Metal Matrix Composites

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The applicability and effectiveness of the representative volume element (RVE) approach for predictions of creep properties in metal matrix composite materials were analyzed numerically in this paper. A special attention was paid to the sensitivity of numerical solutions with respect to the volume element size, in terms of short-term creep strength and secondary creep rate of the model. The numerical models were based on the microstructure of composite material which consisted of creeping matrix with randomly distributed non-creeping hard spherical particles. A modified random sequential adsorption algorithm was applied to reproduce volume elements of composite microstructures. Then, the elements were subjected to creep deformations with uniaxial stress boundary condition. Statistical analysis of numerical experiments for different volume element sizes showed that the effective creep properties can be determined for large volumes of the elements. In both cases of creep strength and secondary creep rate, the statistical fluctuations of the numerical solutions were decreased with increasing volume of element. Several test cases are also presented in order to validate the model against experimental results from literature, and the advantage and limitation of the RVE approach are discussed. [doi:10.2320/matertrans.M2014137]

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1. Introduction

Metal matrix composites (MMCs) reinforced by discontinuous ceramic reinforcements are expected to be applied particularly for high-temperature structural components, because they can maintain their excellent mechanical properties at much higher temperatures than polymer matrix composites.1-6) Since the MMCs are often subjected to stress for long periods of time at elevated temperature, a thorough knowledge of creep behaviors and deformation mechanisms are required for their engineering applications. However, costly and time consuming creep experiments as well as poor machinability of MMCs make it difficult to experimentally evaluate the creep behaviors of MMCs. Thus, the developments of analytical and/or numerical methods for predicting creep behaviors of MMCs are unavoidable.

There have been a number of analytical models developed for predicting the stress state during creep and overall creep deformation behaviors of MMCs. In general, two different methods have been extensively used. The first basically included the Eshelby or “mean stress” theory,6) which treats the strengthening of composites reinforced with elastic ellipsoidal inclusions.8-10) These models assumed that the plastic strain in the matrix was uniform along the loading axis. While these models often provide a useful variation of the creep parameters, they cannot directly represent the actual creep behaviors of the MMCs, because the local state of stress and strain in the matrix is highly heterogeneous in nature. The second analytical modeling method was based on the shear-lag theories,11) in which strengthening was attributed to the load transfer through shear stresses from the matrix to the fiber at the interface along the loading axis.12-14) However, as pointed out by Christman et al.15) and Dragone and Nix,16,17) these modeling approaches had several limitations, such as acute sensitivity to minor parameter changes involved in their derivation, a non-rigorous enforcement of equilibrium with the use of the rule of mixtures, and the inability time-dependent phenomena.

On the other hand, one of the promising ways regarding the micromechanical modeling of creep in MMCs is a use of numerical analyses such as the finite element method (FEM), because there are no restrictions on the geometry, material properties or number of phase in these models. Such approaches involve modeling the composite as two separate materials with distinct material properties. An additional benefit of using numerical analysis is its capability of providing a full field solution of time-dependent problems in a way that is not feasible by an analytical approach. Numerous reports can be found in the literature describing the numerical studies related to the creep of MMCs.16,18-25) However, numerical models published so far in the literature, although they are capable of modeling the details of composite microstructure, were restricted to unit cell approaches in which the real microstructures of the MMCs were approximated by a periodic regular array of single inclusion embedded geometries. Hence, application of such an approach is limited to the regularly arranged reinforcements, although the real microstructures of MMCs are typically random and heterogeneous in nature.

In order to develop an efficient modeling methodology to predict realistic creep response of MMCs with random and heterogeneous microstructures, new attempts based on multi-inclusion FEM have been recently coined by some of the present authors.26,27) The main idea was that creep simulations can be carried out more accurately by models with randomly distributed reinforcements than conventional single-inclusion unit cell models, since the properties of the MMCs rely largely on their reinforcement distributions.
These studies utilized representative volume element (RVE) of the microstructure which consisted of a few tens of randomly distributed reinforcements for the creep simulations of unidirectional SiC short fiber reinforced Al6061 MMC. Throughout the numerical analyses, they found that the creep responses of the numerical models were greatly affected by the arrangement of the short fibers.26 The results of this study pointed out that, attempts to simulate creep response of MMCs must take into account the heterogeneities in microstructure. In a later study,27 they examined the effect of reinforcement clustering on the creep behaviors of MMCs using numerical FEM models. The results of these two studies suggested that the creep deformation behaviors of the MMC can be predicted by multi-inclusion FEM simulations with proper accuracy, when the random and heterogeneous reinforcement distributions in the MMCs are well represented by the numerical RVE models. They also reveals the possibility of evaluating creep behaviors of various MMC systems using multi-inclusion FEM models, since this type of modeling approach is applicable to any kind of MMCs which have random morphologies. However, although some individual comparative studies have been made, there are no complete or detailed numerical analyses of RVE approach using different volume element sizes which are indeed essential in evaluating model applicability and reliability.

It is also important to note that with few exceptions, previous finite element studies of creep in MMCs including the authors' have focused on the prediction and analysis of steady-state creep behaviors thereby neglecting consideration of primary creep deformations in the MMCs. Although these fundamental studies have given valuable information on creep strengthening mechanisms of the MMCs, their results (i.e., steady-state creep rates of the MMCs) are inadequate to characterize creep strength (maximum stress required to cause a specified amount of creep in a specified time) of the MMCs because primary creep represents a significant portion of the total creep strain.28-30 Most of creep-limited applications require high dimensional tolerance during operation, and thus knowledge of residual strain tolerance under high-temperature stress would be more helpful than that of steady-state creep rates to determine a guaranteed life of safe operation for structural parts.31,32 However, as far as the author’s knowledge, currently there are only two numerical studies which considered both primary and steady-state creep of MMCs in the literature20,33 with simple unit cell models.

The present investigation focused on the evaluation of practical applicability of numerical RVE approach on prediction of creep properties of MMCs. The uniaxial creep deformations of randomly distributed spherical particle reinforced composites were investigated numerically by RVE modeling technique with models having different volume element sizes. The statistical fluctuations of creep strength and secondary creep rate of the models were analyzed, and representativity and practical applicability of the RVE approach for the prediction of creep properties were discussed in terms of volume element size. Finally, two different MMCs were modeled as benchmark problems and the numerical creep deformation results were then contrasted with corresponding experimental results from literature for validation purposes.

2. Numerical Model

2.1 Generation of RVEs

Simple spherical particle reinforced MMC is selected to study the general aspect of simulating random composite creep behaviors, since it has relatively simple microstructure and experimental data to validate the numerical model are also available in the literature.34 The creep strains and creep deformation rates of the MMCs were obtained by the finite element analysis of cubic RVEs of volume $L^3$ consisting of randomly distributed non-overlapping particles. The RVEs were generated using the random sequential adsorption (RSA) algorithm35 modified to provide for a minimum distance between neighboring reinforcements. The RSA algorithm used for the generation of the RVEs of the MMCs consisted of adding reinforcement particles sequentially to a cubic space by randomly generating the center point of the reinforcements in 3D space. Intersection of reinforcements was not acceptable during the RSA procedure. Hence, a newly generated candidate particle was deleted if it overlaid any particles that had been generated previously. The minimum distance between the particles were set to one-hundredth of cubic RVE length $L$ for each cases, which was imposed by the practical limitations of creating an adequate finite element mesh in the matrix between particles. The flowchart of the RSA procedure is shown in Fig. 1. The RSA algorithm with the combination of the above conditions was used to generate the RVE models of the MMCs up to the desired volume fractions of particles.

2.2 Finite element analysis

2.2.1 Matrix creep model

In order to study the practical applicability of RVE approach for predicting the creep strength, a creep material model for the matrix creep strain essentially describes both the primary and steady-state creep at given temperatures. In this study, the creep behavior of the matrix was modeled using time hardening creep model36-38 because it is a classical description of rate-dependent behavior and is commonly available as a built-in creep model in commercial finite element software. The creep model chosen in this study is the combined primary-secondary creep form given by the following relationship for the specific temperatures:
uniaxial tensile stresses were applied to each model by analyses. To evaluate models under uniaxial tensile loading were evaluated by of this boundary condition is shown in Fig. 2. The schematic illustration free boundary conditions on the outer surfaces of the cubic RVE models during deformations. The schematic illustration of the boundary condition is employed throughout this study.41 This was imposed by appropriate iso-displacement and shear traction or displacement components.39,40) Among various types of boundary conditions available in the literature, uniform displacement-traction, also called orthogonal-mixed boundary condition is necessary to specify the boundary conditions in terms of uniaxial stress state using micromechanical RVE models, it is necessary to specify the boundary conditions in terms of traction or displacement components.39,40) Among various types of boundary conditions available in the literature, uniform displacement-traction, also called orthogonal-mixed boundary condition is employed throughout this study.41-43) This was imposed by appropriate iso-displacement and shear boundary conditions on the outer surfaces of the cubic RVE models during deformations. The schematic illustration of this boundary condition is shown in Fig. 2.

The overall creep deformation behaviors of the RVE models under uniaxial tensile loading were evaluated by finite element, load controlled geometrically nonlinear analyses. To evaluate x-axis creep response of each model, uniaxial tensile stresses were applied to each model by fixing the displacement of the y-z plane in the x-direction, and applying static loads on the opposite side of the model. In the same manner, y and z-axes creep responses of each model were also calculated for each model.

2.2.2 Boundary conditions

For simulating heterogeneous material behaviors under uniaxial stress state using micromechanical RVE models, it is necessary to specify the boundary conditions in terms of traction or displacement components.39,40) Among various types of boundary conditions available in the literature, uniform displacement-traction, also called orthogonal-mixed boundary condition is employed throughout this study.41-43) This was imposed by appropriate iso-displacement and shear free boundary conditions on the outer surfaces of the cubic RVE models during deformations. The schematic illustration of this boundary condition is shown in Fig. 2.

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2.2.3 Model implementation

For the implementation of the models, commercial finite element software, ANSYS® Version 12, was used throughout this study to solve the numerical problems.44) The calculations were performed on a personal workstation (XW8600, Hewlett-Packard, USA), with eight 3.16 GHz processors and 16GB RAM. The RVE models, which were generated by the RSA algorithm as previously described in Section 2.1, were meshed with ten-noded quadratic tetrahedral elements using automatic meshing algorithm provided by ANSYS (SOLID 187, structural solid element, ANSYS). The meshes were made finer near the interfaces between matrix and reinforcement particles or fibers.

An implicit backward Euler scheme was used for integrating time-dependent formula of creep simulations throughout this study. Further details of this procedure can be found in some of the author’s previous work,26) which will not be repeated here. Due to the non-linearity of the problems, the time step size was monitored during each creep simulation and controlled by keeping the creep ratio (ratio of creep strain to the elastic strain at each time step) under the limit of 1.

3. Numerical Results and Discussions

3.1 Numerical results with different volume element sizes

This subsection investigates the numerical aspects of creep RVE modeling, focusing on the statistical fluctuations of model creep behaviors with regarding size of volume element. Two types of composite creep properties, creep strength and secondary creep rate, were studied with models having different volume element sizes V of the random composite microstructure. The material used for this subsection consisted of creeping matrix alloy and spherical hard particles as a reinforcement phase with a volume fraction of 20%. The microstructure and material properties used in this subsection were based on TiC/(Al-1.5Mg) MMC which was previously investigated by Krajewski et al.34) but generally any particle reinforced MMC material could be also described.

3.1.1 Model geometries and material parameters

Using the RSA procedure described in Section 2.1, the cubic three-dimensional sample microstructures were reproduced for simulating the creep responses. During the RSA procedure the radii of the reinforcing particles were randomly selected within a range 1.5–4.5 µm, similarly to the experimental observation in Ref. 34).

To evaluate practical applicability of RVE approaches in predicting creep behaviors of random composites, statistical analyses have been employed. A series of volume elements with increasing sizes (side lengths L = 5, 10, 15 and 20 µm) were produced, and for each size, three different samples were constructed by RSA procedure with different particle locations. Then, they were subjected to uniaxial tensile creep deformation along the three axes of coordinates: thus, totally nine creep curves were obtained for each size of volume element. The typical geometries and finite element meshes of the models are shown in Fig. 3. Number of elements and node points of these models were about 9,000 and 23,000 for L = 5 µm, 15,000 and 28,000 for L = 10 µm, 29,000 and 75,000 for L = 15 µm and 114,000 and 212,000 for L = 20 µm, respectively. The average numbers of particles in the model increased exponentially with increasing L and, for L = 20, approximately 90 individual particles were fully or partially generated in a 20 · 20 · 20 µm³ cubic space of the volume element.

For finite element simulations, the particles were modeled as linear elastic while an elastic-creep material was used for the matrix phases. The elastic moduli, Poisson’s ratios and

\[ \varepsilon_c = A \alpha^n \tau^m + B \sigma^n t \]  

where \( \varepsilon_c \) represents the creep strain, \( \alpha \) is the equivalent stress of the matrix phase, \( t \) is time, superscripts \( n \) and \( m \) are creep exponent coefficients for primary and secondary creep and \( A \) and \( B \) are constants. There are a total of five creep parameters that should be determined by fitting eq. (1) to the experimental creep data at any given temperature. The first term in right hand side of eq. (1) can be thought of corresponding to the primary creep regime and the second term to the secondary creep regime of matrix material.

![Fig. 2 Schematic illustration of uniform displacement-traction boundary condition. In the figure, dotted and solid lines represent undeformed and deformed 2D bodies, respectively.](image-url)
The coefficients of thermal expansion used for the simulations are listed in Table 1. The creep material parameters in eq. (1) for the matrix were taken from experimental creep data of Al-1.5Mg matrix alloy in Ref. 34. For estimating initial values of the parameters, the steady-state creep portion of the time hardening expression (i.e., second term in right hand side of eq. (1)) was fitted to the steady state creep data of the Al-1.5Mg unreinforced alloy in Ref. 34). The estimated parameters from this step were then used as initial guesses for the next model fitting step. A reasonable fit could be obtained by taking $A = 4.6 \cdot 10^{-7}$ MPa$^{-0.5}$/s$^0.5$, $B = 1 \cdot 10^{-22}$ MPa$^{-7.6}$/s, $n = 0.5$, $m = 7.6$ and $q = 0.45$ in eq. (1), which were used for describing matrix creep deformations in the model.

Because of the thermal expansion mismatch between the reinforcement and the matrix, the considered MMC is expected to have a residual stress after the fabrication process, prior to the creep tests. In Ref. 34), the MMC was annealing heat treated at 371°C before the creep tests. Assuming that the MMC was in stress-free state at the annealing temperature and the residual stress was generated during the cooling after the heat treatment, this effect was considered by taking $\Delta T = 221°C$ (371–150°C, where 371°C was annealing heat treatment temperature used in Ref. 34)).

### Table 1 Mechanical properties of the reinforcement particle and matrix material used for the simulations.

<table>
<thead>
<tr>
<th>Material</th>
<th>Elastic modulus (GPa)</th>
<th>Poisson’s ratio</th>
<th>Coefficient of thermal expansion ($°C^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matrix</td>
<td>70</td>
<td>0.33</td>
<td>$2.4 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>Particle</td>
<td>450</td>
<td>0.185</td>
<td>$7.7 \cdot 10^{-6}$</td>
</tr>
</tbody>
</table>

Fig. 3 Typical model geometries and meshes of FEM models with various cubic volume element length of $L$. (a) $L = 5 µm$, (b) $L = 10 µm$, (c) $L = 15 µm$ and (d) $L = 20 µm$. The reinforcement particles are displayed only for better visualization.

Fig. 4 Creep curves predicted by the models, for an applied load of 50MPa at 150°C with different volume element sizes. (a) $L = 5 µm$, (b) $L = 10 µm$, (c) $L = 15 µm$ and (d) $L = 20 µm$.

#### 3.1.2 Numerical results and discussions

Figures 4(a)–4(d) show the evolutions of creep strains with increasing creep time predicted by the models with different sizes of volume elements. Results are presented for a creep test with applied load of 50 MPa at 150°C. Curves reported in Fig. 4(a) show that discrepancy on creep responses were very large between the nine cases for $L = 5 µm$. This discrepancy...
in creep responses was reduced with increasing the element length $L$, as shown in Fig. 4. The creep curves became almost identical when $L$ is increased up to 15 µm, suggesting that proper isotropy and statistical homogeneity of the models could be achieved by choosing a sufficiently large size of volume element in RVE analysis.

Figure 5 show the evolution of the ensemble averages of predicted creep strains after 400 h with increasing size of the volume elements, where error bars represent the standard deviations of the strains around the mean values. The variation of the creep strains reduced with increasing the size of volume elements. The evolutions of steady-state creep rates as well as their standard deviations are shown in Fig. 6. The fluctuations of steady-state creep rates were also decreased with increasing the volume element size, as expected. The standard deviations in both of the creep strain and the creep rates were less than 5% when $L = 20$ µm, indicating that the volume element with $L = 20$ µm corresponded to reasonable bounds for representing the creep deformation behaviors for the microstructure studied in this section.

As stated by many researcher,45–47 for practical modeling purpose RVEs may practically exist if the apparent values of wanted material property converges to (or tends to stabilize in) a certain value with increasing volume element size. This is because in this case the apparent values will continuously approach to the effective value with increasing volume element size, or (in average) with increasing number of realizations. The results presented in Figs. 4–6 showed suitable statistical results for the existence of a RVE in creep simulations of MMCs. As shown in Figs. 5 and 6, the statistical fluctuations of apparent values for creep strength and the minimum creep rate were both decreased with increasing volume element size. In addition, the model with $L = 20$ µm seems to be sufficiently large for prediction of creep behaviors on this type of MMC microstructure.

### 3.2 Comparison of predicted creep behaviors with experimental observations

The experimental creep results for TiC particle reinforced Aluminum MMCs were simulated by the RVE models in this section. Two sets of experimental data reported by Krajewski et al.34 were used. First, in Section 3.2.1 the model used in the previous section was compared with corresponding experimental results for 20% TiC reinforced Al-1.5Mg MMCs. Next, in Section 3.2.2 a set of experimental results for 15% TiC reinforced pure Al MMCs were considered for the simulations. Finally, the validity and limitations of the RVE model were discussed in Section 3.2.3. It is worth noting that these numerical results are not simulations but predictions of the experiments, since the experimental creep data for the matrix alloys in Ref. 34) has been used to estimate the overall creep responses of the MMCs.

#### 3.2.1 Case I: 20% TiC particle reinforced Al-1.5Mg MMC

The numerical model used in Section 3.1, with $L = 20$ µm, was again considered as a RVE for the TiC/Al-1.5Mg MMC in this section. The material parameters used for the model were also same to Section 3.1. Figure 7(a) illustrates selected creep curves obtained by the model for two different loading conditions of 50 and 60 MPa at 150°C, where corresponding experimental creep curves presented in Ref. 34) for this material are also depicted for comparison. The experimental creep curves of the MMC were reproduced very well with the model. The overall shape of the predicted creep curves represents correct tendency, and the predicted creep strains were also fairly well matched with the experimental results.

Figure 7(b) shows the comparison of the model predictions with experimental data for the same MMC, in terms of the steady-state creep rates versus applied stress. In the figure, the creep rates of the unreinforced Al-1.5Mg alloy34) (open circles) and the creep model for the matrix in the simulations (corresponding solid line) are also plotted for comparison. The numerical data for steady-state creep rates were obtained by a series of creep simulations for different loadings within a range of 50–100 MPa. The experimental creep rates were slightly underestimated by the model, but again agreed fairly well with the model.

#### 3.2.2 Case II: 15% TiC particle reinforced pure Al MMC

The second material examined for the benchmark problem was 15% TiC particle reinforced pure Al MMC, in which the volume fraction of TiC was slightly lower and the creep resistance of the matrix alloy was much inferior compared with the former one. In Ref. 34) the pure Al matrix alloy had nearly no primary creep deformations in its creep curves. Thus the matrix alloy was assumed to be in steady-state creep from the onset of loading by taking $A = 0$ MPa$^{-m}/s$ in eq. (1). The $B$ and $m$ in eq. (1) were considered as $1.5 \cdot 10^{-38}$ MPa$^{-20.8}/s$, and 20.8, respectively.
Before main calculations were carried out, the statistical fluctuations of the numerical creep results were examined with models having different size of volume element by following the same procedure as in Section 3.1. Similar to the former case, it was noted that model with side length \( L = 20 \mu m \) was large enough to representing the creep responses of the MMC which was selected as a RVE in this section. When \( L = 20 \mu m \), the deviations in steady-state creep rates between models were less than 5\% and almost identical creep curves were obtained.

Figure 8(a) shows a comparison of creep curves obtained by the RVE model and experiments\(^3\)\(^4\) for different applied loads at 150°C. In contrast to the case of TiC/Al-1.5Mg MMC, the model for pure Al MMC significantly overestimated the experimental creep strains. The minimum creep rates predicted by the model are plotted in Fig. 8(b) against the applied stress on a double logarithmic scale, showing that the creep rates obtained by the model were much faster than those from the experiments. The creep rates of the unreinforced pure Al\(^3\)\(^4\) (open circles) and the creep model for the matrix in the simulations (corresponding solid line) are also plotted for comparison.

### 3.2.3 Discussions

When non-creeping reinforcement is introduced in MMC, overall creep rate is generally much slower compared with its matrix metal or alloy since the creep deformation of the matrix phase is hindered by the load partitioning effect of the reinforcement. Both of the RVE models studied in this study showed clearly this reinforcing effect: By adding the reinforcement ceramic particles in the models, the creep rates of the composite models were reduced significantly compared to the unreinforced alloy, as shown in Figs. 7 and 8. On the other hand, from a quantitative point of view the models showed very different degree of prediction accuracy when compared to their corresponding experiments.

The first results for the TiC/Al-1.5Mg MMC in Fig. 7 showed that the RVE model could give reasonable predictions of creep deformation behaviors of MMCs. This might seem surprising but can be explained by the fact that the RVE was chosen such that it could contain enough information on the microstructure which would be large enough to be representative of the material creep behavior. However, in the second case of pure Al MMC the RVE model overestimated greatly the creep strain and rate compared with the experiments (Fig. 8).

Interestingly, a previous numerical analysis by Krajewski et al.\(^3\)\(^4\) also showed similar results to those obtained from the present RVE models. They used simple unit cell model to analyze creep improvement effect by TiC particle on the same pure Al matrix MMC, and have concluded that numerical models incorporating the experimentally determined creep behavior of unreinforced pure aluminum are unable to predict the experimentally observed creep improvement by TiC particle in the MMC. A possible reason for this inconsistent model prediction was that the microstructure and creep properties of the pure Al matrix phase was different when compared with the unreinforced one, which was revealed by the transmission electron microscopy (TEM) study of this material.\(^3\)\(^4\) Their TEM observations suggested that, unlike in the case of TiC/Al-1.5Mg MMC, the grain size of the pure Al matrix in the MMC was significantly larger than in the unreinforced one, which could result in very

![Fig. 7 Comparisons between RVE model and experiment for 20% TiC particle reinforced Al-1.5Mg MMC, in terms of (a) creep strains with several loadings at 150°C and (b) steady-state creep rates.](image1)

![Fig. 8 Comparisons between RVE model and experiment for 15% TiC particle reinforced pure Al MMC, in terms of (a) creep strains with several loadings at 150°C and (b) minimum creep rates.](image2)
different creep properties by changing the major creep mechanism of the aluminum. The same explanation can be applied to the results in Fig. 8, since the matrix creep parameters of the RVE model in this study were also based on the same experimental creep data of the unreinforced pure aluminum.

4. Summary and Conclusions

The practical applicability and limitation of RVE modeling approach on prediction of creep properties of MMCs were investigated by the simple numerical tests of creep deformations in random particle MMC. An existence of RVE to the problem of simulating creep deformations was firstly worked out using statistical analysis of numerical models with different volume element sizes. The analysis results showed that statistical fluctuations in both creep strengths and creep rates obtained by the models reduced with increasing the volume element size. In the case of the 20% spherical TiC particle reinforced Al-1.5Mg MMC which was considered here, the standard deviations of both creep strength and creep rate were less than 5% when the length of cubic volume element was 20 μm. The amount of errors in this case is considerably small and is probably acceptable for determining a guaranteed life of safe operation for most of creep-limited applications. Thus, one can conclude that the RVEs can practically exist for the predictions of both creep strength and creep rate of MMCs with random microstructures.

The RVE models were then applied on two different TiC/Al MMCs, and their numerical results were compared with experimental data for determining the potential of using this modeling technique. The experimental creep data of unreinforced matrix were used for determining the matrix creep parameters in the models. The models fitted well to the experimental data in the case of TiC/Al-1.5Mg MMC, showing potential of the RVE models for predicting creep behaviors of MMCs. However, in the case of TiC particle reinforced pure Al MMC, the model greatly overestimated the experimentally observed creep strain and rate. One possible reason for this large discrepancy is that the creep mechanism of pure Al changed with addition of reinforcing TiC particles, which was previously also suggested by TEM observations.

The main conclusion to be drawn from the numerical analysis and discussion was that RVE modeling technique could be presumably utilized for predicting and understanding the creep behaviors of MMCs. Since more complex and realistic microstructure can be modeled and considered by using the RVE technique compared to the conventional unit cell or simple micromechanical approaches, it can be very useful tool for design and optimization purpose. This kind of model can be also used to simulate creep response for various types of artificial MMC microstructures, since there are no restrictions on the geometry, material properties or number of phase in the RVE models. Such a study may provide microstructure-properties relations of MMCs, which are worthwhile and merit further research. However, the practical application of the RVE model is perhaps limited to cases that the actual creep behavior of the matrix phase can be accurately estimated by the unreinforced metal or alloy which is processed by the same condition of the MMC. If there is a significant difference in creep character between a matrix phase in MMC and the unreinforced matrix material, the RVE model is practically hard to be used for predicting the creep behavior of the MMC because of the inaccessibility of the matrix creep parameters.

REFERENCES