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Effects of Clustering and Shape of Particles on the Mechanical Behavior of Al-B_4C Metal Matrix Composites

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Abstract—*The influences of particle distribution on the mechanical behavior of Al-B_4C composites is investigated in the present work. Al-B_4C composites having 4, 8 and 12 vol% B_4C are fabricated using squeeze liquid stir casting method and experimentally characterized for their effective elastic moduli. Next, the influences of clustering of particles and the shape of particles, on the effective elastic moduli are investigated using three dimensional finite element method. 3D representative volume elements (RVEs) are generated considering icosahedron shaped particles. In order to investigate the clustering influences, three models were established including one-clustering, two-clustering and random particles arrangement. Al matrix is modeled as elastoplastic material and B_4C is modeled as linear elastic material. The results obtained are compared with the experimental values. The effects of number of clustered particles are further examined. It is observed that the effective elastic modulus is highly sensitive towards the clustering of particles. The distribution of maximum principal stress and the hydrostatic stress are studied by plotting the contours. The results reveal that the clustering lead to more heterogeneous distribution of stresses in composite microstructure.*

1. INTRODUCTION

Particle reinforced metal matrix composites (MMC) exhibit markedly higher stiffness and strength compared with the unreinforced metals and alloys. These composites are extensively used in automotive, aircraft and aerospace applications [1-5]. The fabrication techniques have been also well evolved in recent years, such as such as powder processing, squeeze casting, extrusion process and liquid infiltration. The spatial distribution of particles in metal matrix significantly influences the mechanical properties of MMCs. However, obtaining a uniform homogenous distribution of reinforced particles is often difficult. The reinforcement of boron carbide in aluminum matrix often results into non-uniform distribution due to poor wettability and comparable densities of aluminum and boron carbide [6,7].

The reported experimental work show that the spatial arrangement of reinforced particles is one of the deciding factor of yield strength, ductility, fatigue and fracture behavior of MMCs [8-10]. The behavior of MMCs having clustered distribution of particles is still poorly understood, although, there is a wide spread consensus that the microstructures with particle clustering tend to result in poorer mechanical properties. Different methods are used to model the mechanical behavior of MMCs. Some of these methods are analytical and rely on the equivalent inclusion method of Eshelby [11] and their mean-field extensions [12–14]. The tangent-based [5,6] and secant based [7,8] homogenization approaches are found to be relatively successful in describing the non-linear behavior of the composite materials, however, in case of composites containing clustered distribution the stress state of particles are difficult to analyze with these models.

In order to investigate the analytical homogenization models to obtain insight into the local evolution of the stress state within the matrix and particles for a specific microstructure, finite-element methods (FEM) have been employed [15-17]. Unlike the analytical approaches, FE methods can be used to account for non-uniform particle distributions that are encountered in practice. In the present work, 3D-FEM is used to investigate the effects of particle clustering on the mechanical behavior of Al-B4C MMCs. The effective elastic module is computed and the results are compared with the experimental values.

2. MATERIALS AND EXPERIMENTAL PROCEDURE

Three different samples of Al-B_4C composites, having 4, 8 and 12 vol% boron carbide reinforced into pure aluminum matrix were fabricated using squeeze casting method in a bottom pouring type stir casting furnace. Aluminum ingots, with 99.5 % pure aluminum and boron carbide powder of 200 mesh size were used. The microstructure of fabricated composites were studied using scanning electron microscope and the effective elastic moduli were measured at room temperature as well as at elevated temperatures. The details of fabrication can be seen elsewhere [7]. In the present work the FE analysis of 8 vol% composite is conducted. The SEM image of 8 vol% composite show the clustering of particles (see Fig. 1)

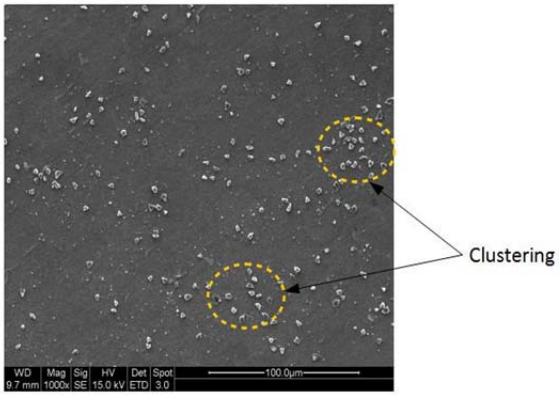


Fig. 1 SEM image of 8 vol% Al-B4C composite

3. THREE DIMENSIONAL FINITE ELEMENT ANALYSIS

3.1 Microstructural modeling

In order to model the composite's microstructure, 3D RVEs were generated by running a python script based on random sequential algorithm, in Abaqus software. In order to generate the RVEs, 50 number of icosahedron particles were used. Icosahedron particles are selected to model the complex shaped particles. The RVEs were generated considering uniform random distribution, single clustered and double clustered distribution of particles (see Fig. 2). The matrix and the reinforcement phase were assumed to be perfectly bonded. The generated RVEs were meshed in Abaqus software. 10-node tetrahedral elements (C3D10M) were used to mesh the RVEs. C3D10M being a second order element, can model the 3D stress state involving elastoplastic deformation in an accurate manner. A mesh sensitivity analysis was conducted to determine the optimum seed size and a seed of 0.05 with RVE side length of 1 mm was used.

3.2 Boundary Conditions

In order to calculate the effective elastic moduli, the periodic boundary conditions were assigned as:

Initial strain: $\varepsilon_{xx} = 0$

Peak Strain: $\varepsilon_{peak} = 0.01$

The volumetric mean of stresses (σ_{mean}) and strains (ε_{mean}) at integration points of RVE were computed. The effective elastic moduli were computed as:

$$E = \frac{\sigma_{mean}}{\varepsilon_{mean}}$$

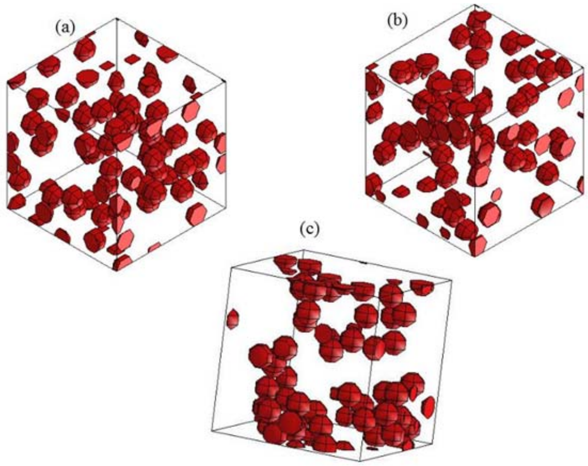


Fig. 2 RVEs for 3D FEM analysis, (a) uniform distribution, (b) one-cluster and (c) two-cluster

4. RESULTS AND DISCUSSION

4.1 Effective elastic modulus

The measured elastic modulus from 3D FE modeling are compared with the experimental values in Fig. 3.

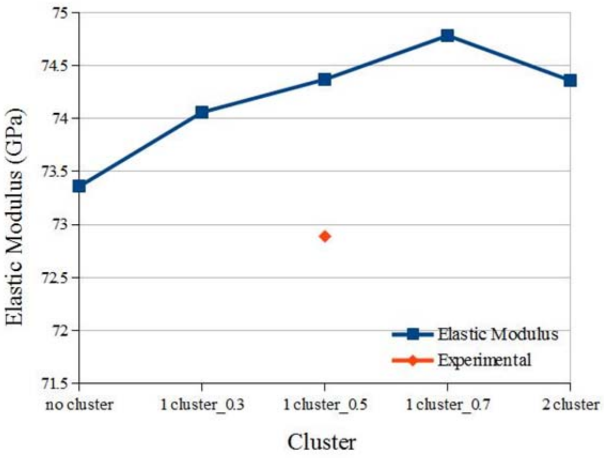


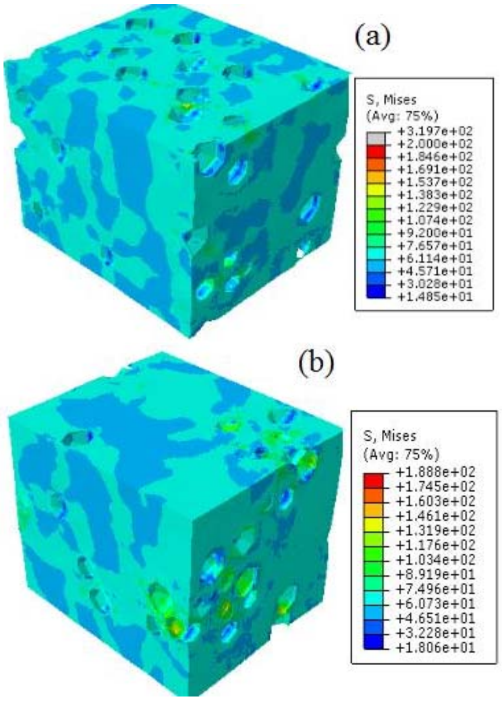
Fig. 2 Effective elastic moduli modeled using FEM

Three different models, containing uniform distribution (no clustering), 1 cluster and 2 clusters are created.

The 1 cluster model is studied further by increasing the relative volume fraction of clustered particles as: 30%, 50% and 70%.It can be observed that the effective elastic modulus of composites is higher in case of clustering. This effect of clustering of particles is more pronounced in case of single cluster. Further, the elastic modulus, in case of single cluster, increases as the relative fraction of clustered particles increases. The predicted modulus is slightly higher than the experimental values. It is due to the presence of voids and thermal residual stresses that is not considered here [6] to keep the analysis simple.

4.2 Stress and Strain Distribution

In order to study the effects of particle clustering on the stress and strain distribution in the matrix and particles, the stress and strain field in the matrix and the particles are plotted in contours. Fig.4 (a)-(f) show the contour plots of the von Mises effective stress in the matrix and reinforced particles. From Fig.4a and Fig.4b, it can be apparently found that the stress field in the particle clustering is very inhomogeneous due to the mismatch of elastic modulus between the matrix and the particles. At the tip of the particles along the loading direction, the von Mises effective stress is higher. A high stress concentration can be observed in Fig. 4 (a)-(c) at the junction of matrix and particles. It is evident from Fig.4c that the von Mises effective stress of the matrix is much more homogeneous than those in Fig.4a and Fig.4b due to the different particle distributions. It can be seen that the von Mises effective stress in the particles is greater than that in the matrix, which shows the obvious strengthening effect.



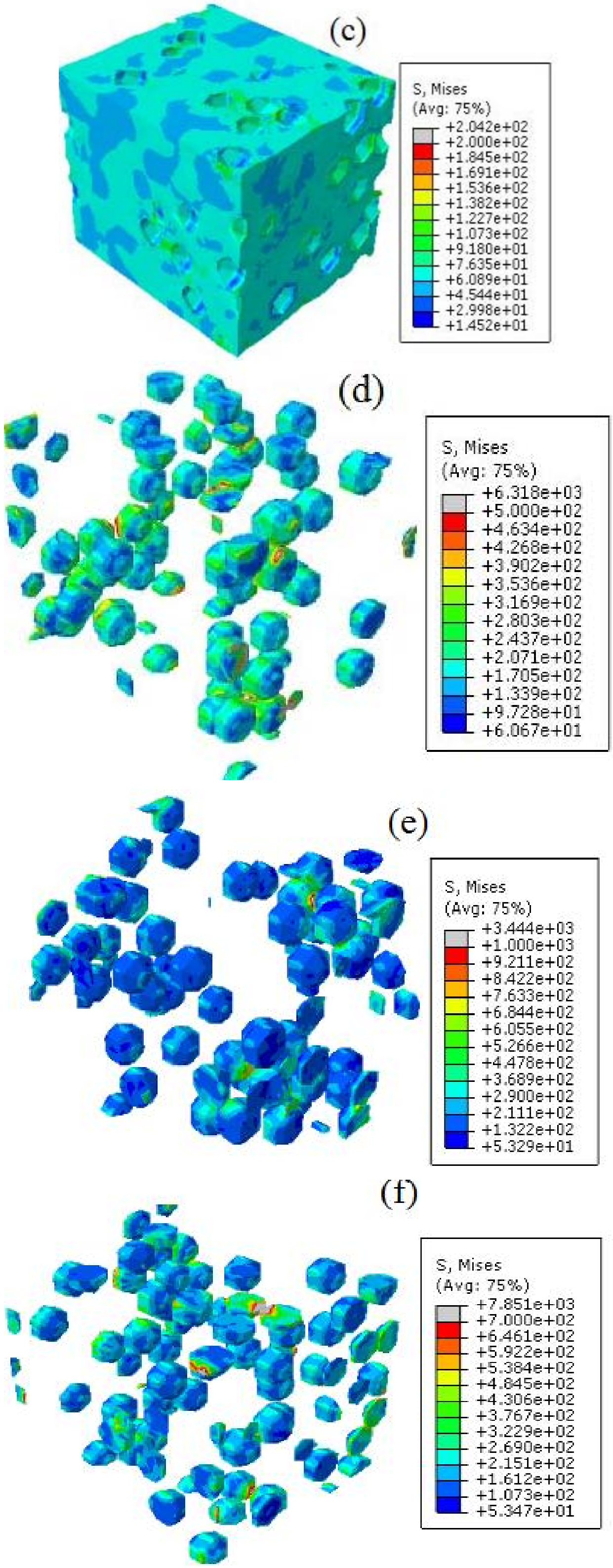
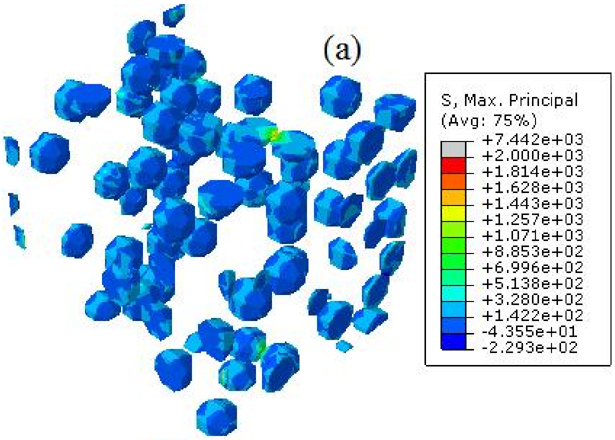


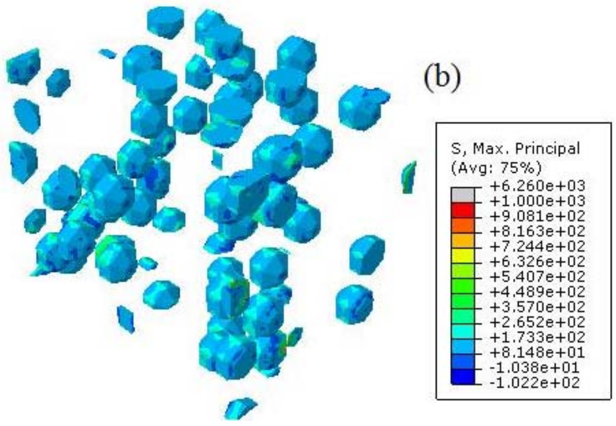
Fig. 4 Effective von Mises stress distribution (a) one-cluster matrix, (b) two-cluster matrix, (c) uniform distribution matrix (d) one-cluster particles, (b) two-cluster particles, (a) uniform distribution particles

Furthermore, the local stress near the tip of the particle in loading direction is much higher than the average stress during tensile deformation. It can be seen that as the particles tend to cluster, it reduces the maximum stress in particles. With respect to the maximum von Mises effective stress in particles, it is evident from Fig.4 that the maximum von Mises effective stress is 6318 MPa in one-clustering and 3444 MPa in two-clustering and they are significantly lower than the maximum von Mises effective stress of 7851 MPa in random distribution. This suggest that the strengthening effect imparted by reinforced particles reduces as they tend to cluster.

4.3 Maximum principal stress

The reinforced particles impart strength by load bearing as well as by restricting the dislocation of particles. The strong interfacial bonding between constituents can results into particle cracking. Maximum principle stress provide important insight about failure mode of particles. Fig. 5 show the distribution of maximum principle stress in boron carbide particles. It can be seen that the clustering of particles results into lower maximum principle stress. The maximum value of maximum principle stress are 7442 MPa, 6260 MPa and 2946 MPa. Therefore in case of uniform distribution, the particles carry higher maximum principle stresses. In order to understand this the equivalent plastic strain in matrix phase is plotted in Fig. 6.





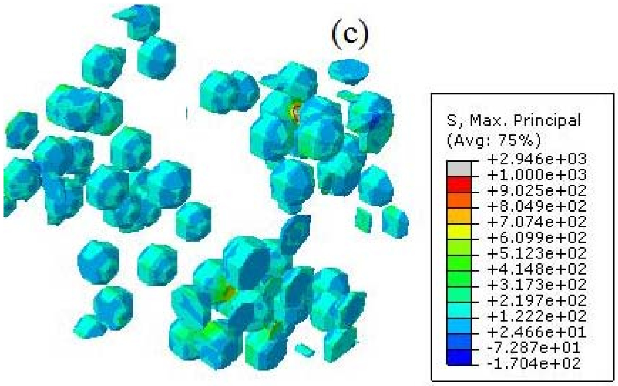
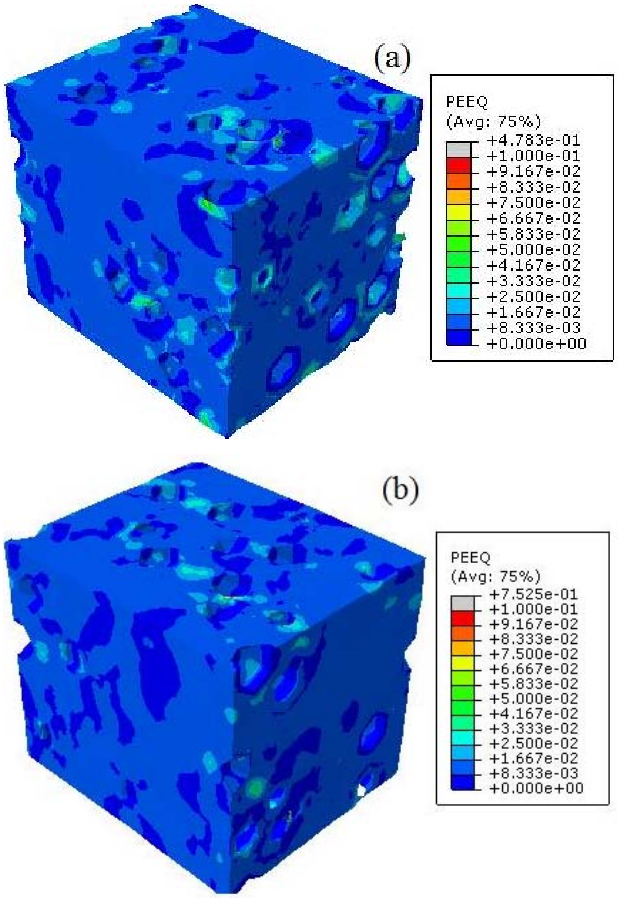


Fig. 5 Maximum principle stress (a) uniform distribution, (b) one-cluster and (c) two-cluster

It can be observed that the maximum equivalent plastic strain induced in one-cluster is 0.7525 and two-cluster is 0.7747 that is much higher than that of uniform distribution which is 0.4783. It is important to observe that the maximum values of plastic strain are observed near the location of clustered particles. Therefore the matrix starts yielding much earlier in case of clustered distribution resulting in higher strain values and lower stress values.



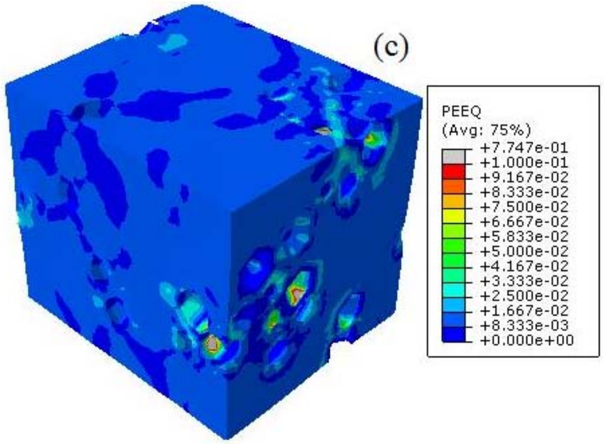


Fig. 6 Equivalent plastic strain in matrix (a) uniform distribution (b) one-cluster and (c) two-cluster

5. CONCLUSION

The effects of particle distribution on the effective mechanical behavior of Al-B$_4$C composite is studied using 3D finite element method by generating the RVEs containing uniform distributed, one-cluster and two-cluster particles.

We observed that the effective elastic moduli increases as the volume fraction of clustered particles increases. The difference between the predicted modulus and the experimental values is due to the presence of voids and residual stresses. The distribution of von Mises stress is studied by plotting the stress contours. We observed, that in case of uniform distribution, the particles carry higher von Mises stress. This show that the particles can impart greater strengthening effect to the matrix by uniformly distributing in matrix phase.

It is noticed that the equivalent plastic strains in case of clustered distribution has higher values. This shows that matrix phase starts yielding at lower stresses in case of clustered distribution due to which the overall stress in composite microstructure subside. The particle failure can be judged from the maximum principle stresses

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