Determination of effective elastic properties of metal matrix composites with damage particulates using homogenization method

S Z Halim, K S Basaruddin, I Ibrahim, M S Abdul Majid and M J M Ridzuan
School of Mechatronic Engineering, Universiti Malaysia Perlis, Pauh Putra Campus, 02600 Arau, Perlis, Malaysia.
khsalleh@unimap.edu.my

Abstract. The present study aims to investigate the effect of micro-damage in particulates metal matrix composite on the elastic properties. The micro damage that perhaps could occurs during manufacturing process or due to environmental effects was modelled in three different types, namely shattered, debonded and breakage particulates with variation of volume fraction. The modelling and analysis were conducted based on homogenization theory by utilizing multiscale finite element software (Voxelxon). The results suggest that the elastic properties of metal matrix composite was sensitive to the geometrical defects of its particle.

1. Introduction
Metal matrix composite (MMCs) is a combination of at least two or more materials. The materials consist of metal that combine with another metal or materials. Matrix is a monolithic material where the reinforcement of MMCs is embedded and completely continuous. The reinforcement is used to change the physical properties of the MMC such as the friction coefficient. The invention of MMC is to reinforce the existence metal particles by improved the mechanical properties of MMC such as the Shear modulus, Young’s modulus, and Poisson’s ratio. The process state of metal matrix composite is divided into three types that are solid, liquid and vapour state. For solid, the forming method can be powder blended and stir casting method is applied in liquid state of MMC. In addition, physical vapour deposition is the method in forming the MMC in vapour state. MMCs are normally acts as a structural usage material to support loading and also to sustain the environmental effect for a long time. The metal of the metal matrix composite can be zinc, magnesium, titanium, copper, nickel iron and cobalt. For example, the aluminium-silicon carbide is metal matrix composite where the silicon carbide been added into aluminium and change from metal to composite.

By adding the silicon carbide, the elastic modulus of the composite will with the same density. In means, the density would not change. The common particles reinforced MMCs such as SiC and Al are usually used in the field of automobile and aviation. Besides, MMCs are normally in the characteristics of low density but high in strength, specific modulus and fatigue resistance. These characteristics are influenced by the arrangement of the particles, shape and size of the particles. The mechanical properties of MMCs can be determined from some analysis for the micro structure of the material. Based on previous study [1] the potential of MMC in improving the mechanical properties of materials with monolithic alloys has been considered as an interest in MMC. Mostly, it was also being considered in the increases of the specific mechanical properties. The general degradation in the properties of fracture also have been compiled by these improvement. The damage of MMC can be affected during manufacturing process or due to environmental temperature. The common types of
damage that exist were void, crack, debonding and shattered in particles of the metal matrix composites [2,3,4]. These damage of particles in metal matrix composites also usually occurs when during mechanical testing on MMC. At different metal matrix composite being test, the different types of damage also will occurs [5, 6, 7]. For instance of metal matrix composites of aluminium and silicon carbide three tests which were fatigue test, creep test and monoatomic loading being conducted to the metal matrix composites shows voids, small crack nucleation, dominant cracks propagation and also fatigue damage. The fatigue damage was usually occurred when there was a formation around particles due to single slip bands.

In addition, damage also would appears in the bulk of material and it types would be depends on anisotropy of the material. The nature of material, size, length and type of draping plays an important role in anisotropy of the material. In composites, damage can occurs for the first 20% of fatigue life with more than 50% and can withstand the presence of crack [8, 9, 10]. In increasing the mechanical properties such as strength and stiffness usually depends on the improvement of the material properties. The relation in degradation on properties of fracture also can improve the mechanical properties such as the ductility and toughness[11]. Based on previous studies, the microstructural parameters were have effects on mechanical properties. The increasing of the volume fraction will increased the modulus, yield and the ultimate tensile stresses but the strain to failure would reduce in a shear-lag-type models. Besides, the increasing in particle size effects the fracture mechanism by changing the particles decohesion into particle cracking [11, 12].

Bian and Wong [4] have studied about the influenced of particle size and volume fraction on the micro damage composites. The bulk and shear modulus of the metal matrix composite have been modified with various volume fraction of particles. Besides, by introducing a new model and modified modulus, the effect of size particles on stress-strain relation under damage of debonding can be predicted. Fatigue was one of the factors in failure of metal matrix composites. It can occurs and lead to the failure of structures under certain loading conditions. Besides, fatigue fracture may occur by the environment condition, faulty design, types of stress and presence of manufacturing defects. A lower compressions resistance than tensile resistance of the composite material under static loading also lead to fatigue when the parameter of fatigue influenced by the viscosity and ductility of the matrix composite [8, 13, 14]. Gupta et al. [15] studied about the failure mode of the SiC that being reinforced with Al due to its interfacial characteristics. The pre-information was about the effect in different cycles of heat treatment. Heat treatment in a cast of 6061 Al/SiC were conducted based on the variation of MMCs.

The damage in particles may be occurs during the manufacturing process of metal matrix composite (MMC) or due to the environmental effects. Damage of particles also may occur when the metal matrix composite is being subjected to a large deformation such as plastic deformation. The types of damage in particles of MMCs that usually occurs during the manufacturing process are shattered, debonding and breakage particles. Thus, the purpose of this study is to investigate the effect in micro-damage of particulate of MMC on its elastic properties. Through homogenisation method, the distribution of the metal matrix can be determined. Thus, the mechanical properties of the MMCs with damage also can be determined.

2. Computational modelling

2.1 Periodic microstructure

Four models been developed through CATIA software with variation of damage and volume fraction to carry out the analysis of how damage occurs in MMC of Aluminium and Silicon Carbide. The periodic microstructure of metal matrix composite can be imagine as in figure 1.
As demonstrative computation, aluminium was chosen as constituent for matrix and silicon carbide (SiC) for the particles. Three modes of damages in particle were developed namely, breakage, debonded and shattered. Additional of one model of MMC with undamaged particles to compare the properties of damage and undamaged MMCs. For variation of volume fraction, four types of metal matrix composite with different condition of particles were modelled in three different diameters of particles as in figure 2.

2.2 Convergence test
The convergence test was conducted by referring to the selected size of voxel element mesh to get the finest results. But the problem arise when the size element of 0.05 show error in received result due to the software limits. It was generally known that the smallest size of element tend to take longer time to be compute or need a powerful workstation in order to make it successfully done. Thus the voxel size was decided to the minimum size of 0.1 for all model with element type of cubical voxel to be analyse using Voxelcon software. Figure 3 shows the view of meshed model. The software generates the polyhedral mesh that can approximate the geometric domain of the model. The voxels, volume, voxel space and voxel size were shown out in the interface of the software.
2.3 Mechanical properties of constituents

The mechanical properties of the material will be calculated by Voxelcon software. The analysis regarding the details of micro structure from the models that have been developed from CATIA software will be done by Voxelcon. The files of models need to save as .stl format in order to export into the Voxelcon software. Type of MMC that had chosen for this research is aluminium metal compose with silicon carbide. The mechanical properties in this research was decided based on previous study [16] about the damage particles in metal matrix composite. It was clearly stated in table 1 as a summarization for the properties of selected constituents to be analysed.

**Table 1**: Micro properties of MMCs [16]

| Material       | Young’s modulus (MPa) | Poisson’s Ratio |
|----------------|-----------------------|-----------------|
| Aluminium      | 70                    | 0.33            |
| Silicon Carbide| 430                   | 0.22            |

2.4 Homogenization method

Homogenization analysis will be carry out in this research. A unit of cell of metal matrix composite will be taken as a representative element volume in applying the homogenization method. The representative element volume will be chosen from each model of metal matrix composite as the best since it can represents the whole micro structure of the composite. The selection of the representative element volume due to the behaviour of the metal matrix composite that have heterogeneous type of microstructure. By using homogenization method, the behaviour of the whole material can be determined and simplified to be considered as an idealised unit cell.

The microstructure size and local region being periodically array assumed to be smaller than global body [17]. The periodicity of the microstructure was remained in the local region after the load was applied and the large deformed occurs. The method of homogenization usually occurs in large deformation problem that can be solved when the microstructure was stated by element. The heterogeneous material can be replaced by equivalent homogenized model with periodically repeated element [18, 19].

The homogenization method being formulated by describing the theory of large deformation and followed by two coordinate system which was microscopic \((x)\) and microscopic \((y)\). Then, the theory of conventional linear homogenization can be derived. By using two scale singular perturbation theory, all equations were followed based on previous studies [17,20].

\[
u_i(x,y) = u_i^0(x) + \varepsilon u_i^1(x, y)
\]

(1)

In this equation, \(u_i^0\) is the microscopic displacement and \(u_i^1\) is a perturbed term due to the microscopic heterogeneity. We suppose applied the traction \(t_i\) on the boundary \(\Gamma\) and neglected the body force. An elastic tensor is denoted as \(X\). By taking \(\varepsilon \to 0\) in homogenization, the decoupled microscopic and macroscopic equations can be obtained.

\[
u_i^1(x, y) = -\chi_{ikh}^h \frac{\partial u_0^k(x)}{\partial x_h}
\]

(2)

\(\chi_{ikh}^h\) is a characteristic displacement that is a periodic function with respect to the microscale. The microscopic equation to solve for the unit cell \(Y\) under the periodic boundary condition is as follows:

\[
\int_Y (E_{ijkh} - E_{ijmn} \frac{\partial x_{kh}^h}{\partial y_n}) \frac{\partial v_i^1}{\partial y_j} \, dY = 0 \quad \forall v_i^1
\]

(3)

Due to the existence of the solution equation (3), the macroscopic equation can be derived as below:

\[
\int_\Omega E_{ijkh} \frac{\partial u_0^k}{\partial x_h} \frac{\partial v_i^1}{\partial x_j} \, d\Omega = \int_\Gamma t_i v_0^1 \, d\Gamma \quad \forall v_0^1
\]

(4)

Where \(E_{ijkh}^H\) is the homogenized elasticity tensor that is also symmetric defined by,

\[
E_{ijkh}^H = \frac{1}{|Y|} \int_Y (E_{ijkh} - E_{ijmn} \frac{\partial x_{kh}^h}{\partial y_n}) \, dY
\]

(5)

Where \(|Y|\) is the volume of the unit cell.
3. Results and discussion
There are three model have been developed in order to investigate the effect of the variation of volume fraction on mechanical properties behaviour of MMCs. The particles of MMCs were divided into four categories which are undamaged, shattered, breakage and debonding model. Besides, homogenisation analysis also has been done by using the same procedure and setting to each model. The results were shown in a linear graph of Young’s modulus against volume fraction as in figure 4 while graph of Poisson’s ratio versus volume fraction as in figure 5, and graph of Shear modulus against volume fraction in figure 6.

Figure 4: Young’s modulus against volume fraction (a) : Young’s modulus, $E_{11}$ against volume fraction, (b) : Young’s modulus, $E_{22}$ against volume fraction, (c) : Young’s modulus, $E_{33}$ against volume fraction.

Figure 4(a) shows the graph of Young’s modulus, $E_{11}$ versus volume fraction of each model. Based on the graph, three types of metal matrix composite model show the incline value while model of debonding shows the decline value of the Young’s modulus, $E_{11}$. The coefficient of determination, $R^2$ for the linear correlation plot of undamaged, debonding, shattered and breakage were 1.000, 0.8849, 0.8670, and 0.8357. From figure 4(b), it shows that three model of metal matrix composite that were undamaged, shattered and breakage which have an increased in Young’s modulus, $E_{22}$ value but decreased value for debonding model. The coefficient of determination, $R^2$ for the linear correlation plot of undamaged, debonding, shattered and breakage were 0.9975, 0.8894, 0.8670, and 0.8687. Based on figure 4(c), the graph shows that an increasing value of Young’s modulus, $E_{33}$ for undamaged and shattered model while the value for debonding and breakage model were fluctuated. The coefficient of determination, $R^2$ for the linear correlation plot of undamaged, debonding, shattered and breakage were 0.9963, 0.3668, 0.8397 and 0.0649.
Figure 5: Poisson’s ratio against volume fraction (a) : Poisson’s ratio, \( v_{12} \) against volume fraction, (b) : Poisson’s ratio, \( v_{23} \) against volume fraction, (c) : Poisson’s ratio, \( v_{31} \) against volume fraction.

Figure 5(a) shows the graph of Poisson’s ratio versus volume fraction. Based on the graph, it can be seen that there was a declined value of Poisson’s ratio for each type of micro damage model. The coefficient of determination, \( R^2 \) for the linear correlation plot of undamaged, debonding, shattered and breakage were 0.9969, 0.8358, 0.9423, and 0.9969.

In Figure 5(b), the graph of Poisson’s ratio against volume fraction shows that the value of Poisson’s ratio, \( v_{23} \) for debonding and breakage model are declined while the value for undamaged and shattered model were constant. The coefficient of determination, \( R^2 \) for the linear correlation plot of undamaged, debonding, shattered and breakage were 0.9643, 0.9968, 0.7546 and 0.8868.

Figure 5(c) shows the graph of Poisson’s ratio versus volume fraction. Three model of micro damage that are undamaged, shattered and breakage show that their Poisson’s ratio, \( v_{31} \) were linearly decreased while debonding was linearly increase. The coefficient of determination, \( R^2 \) for the linear correlation plot of undamaged, debonding, shattered and breakage were 0.9784, 0.9991, 0.9919 and 0.0858.
Based on figure 6(a), shear modulus, \( G_{12} \) of three micro damage model of metal matrix composite that are undamaged, shattered and breakage were linearly inclined as the volume fraction was increased. The coefficient of determination, \( R^2 \) for the linear correlation plot of undamaged, debonding, shattered and breakage were 1.0000, 0.8729, 0.8476, and 0.9034.

Shear modulus, \( G_{23} \) of undamaged, shattered and breakage model of metal matrix composite that shown as in figure 6(b) were linearly increased as the value of volume fraction was increased while shear modulus of debonding model was directly decreased even as the volume fraction was increased. The coefficient of determination, \( R^2 \) for the linear correlation plot of undamaged, debonding, shattered and breakage were 0.9990, 0.8553, 0.8403 and 0.4956.

Shear modulus, \( G_{31} \) of undamaged, shattered and breakage model of metal matrix composite that shown as in figure 6(c) were linearly increased as the value of volume fraction was increased while shear modulus of debonding model was directly decreased even as the volume fraction was increased. The coefficient of determination, \( R^2 \) for the linear correlation plot of undamaged, debonding, shattered and breakage were 0.9990, 0.8553, 0.8403 and 0.4956.

4. Conclusion
Through this study, the results of analysis by using finite element method (FEM) software showing that the particles with regular arrangement and bigger size of damage particle obtain greater elastic modulus. Therefore, by knowing the variation of particles in terms of particles arrangement, size and shape, the mechanical properties of metal matrix composite can be predicted. It is important to know the mechanical properties of metal matrix composite because by knowing this metal matrix composite with optimized mechanical characteristics will able to be manufactured for certain application without any damage occurs.

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