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# An Energy Approach for Determining the Effective Mechanical Properties of Particulate-Reinforced Metal Matrix Composites

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## ABSTRACT

A significant challenge to the determination of particulate-reinforced metal matrix composites (PRMMCs)'s effective mechanical properties is the lack of conveniently approximating techniques. With this reason, an energy approach has been employed to develop the simple relationships between the mechanical properties, such as the modulus of elasticity and the yield stress, of PRMMCs and the corresponding properties of unreinforced matrix materials together with volume fractions of reinforcement. Thus, given the necessary mechanical properties of a matrix material and the volume fraction of reinforcing particles, such the PRMMC's effective properties can be easily predicted. However, after applying the relationships adopted to test with an aluminium matrix alloy, AA6061, reinforced by the silicon carbide (SiC) particulate over a range of reinforcement volume fractions, i.e. from 10% to 40%, the predicted values show a poor approximation when compared with the experimental data. For the case of modulus of elasticity, they tend to give rise to more discrepancies with increasing volume fractions of reinforcement. Similar situations are also observed in case of yield stress predictions, especially when the volume fraction values beyond 20%. Due to the rigid-perfectly plastic behavior assumption of the composite materials considered, the variation of yield stresses determined by such an energy method provide the overestimation to the data those obtained from experiments.


**Key words:** energy approach, modulus of elasticity, yield stress, particulate-reinforced MMCs, AA6061/SiCp

## INTRODUCTION

Metal matrix composites (MMCs) are a broad family of materials aimed at achieving an enhanced combination of properties. The addition of a ceramic reinforcement phase in monolithic metal alloys significantly alters their mechanical and physical properties, as well as deformation behaviour. With proper control, this alteration can be exploited to increase the performance of metal alloys. To date, the attainment of higher strength and stiffness has been the prime motive behind the development of MMCs. Other important improvements in parameters, such as density, wear resistance, thermal expansion and resistance to high temperatures, can be achieved by suitable selection of reinforcements and metallic matrices. At the same time, the desirable properties of metal alloys such as workability, ductility, and high thermal and electrical conductivity should preferably be maintained. Furthermore, the desired combination of properties needs to be obtained at lowest cost.

Particulate-reinforced metal matrix

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composites (PRMMCs) are one class of MMCs. They generally comprise of a ductile metallic alloy reinforced with a hard ceramic reinforcing material in the form of particles by a variety of sizes and shapes. As most PRMMCs consist of constituents not at equilibrium with each other, there is clearly potential for matrix-reinforcement reactions to occur. Control of such reactions and the avoidance of reinforcement degradation during the production and application of these materials are of great importance.

Although there are well established techniques based on analytical schemes for calculating the mechanical properties of particulate-reinforced composites (for example, Withers *et al.*, 1989; Castaneda, 1991; Willis, 1991; Corbin and Wilkinson, 1994). Getting the results from direct computations with these theories may be a demanding task as they are quite complicated in formulation. Hence, a simplified model that gives a reasonable approximation to the experimental data is developed in the present work. Based on an energy approach, simple relationships between the effective mechanical properties, such as the modulus of elasticity and the yield stress of PRMMCs, and properties of unreinforced matrix materials together with volume fractions of reinforcement are established to use in the context of predictions.

## MATERIALS AND METHODS

### Detailed derivation of predicting equations based on an energy approach

As has been expressed earlier, it is useful to establish relationships between the mechanical properties such as the modulus of elasticity and the yield stress of the PRMMC material and the unreinforced matrix material with volume fraction of reinforcement. These enable the PRMMC's mechanical properties to be predicted, provided the corresponding properties of the unreinforced matrix material and the volume fractions of reinforcement are known. Consequently, details of the derivation of relationships adopted can be represented in the current section, as follows:

In Figure 1, a homogenized PRMMC material rod with length, $L$ , is shown. Similarly, a corresponding rod, representing the PRMMC material at the microscopic level, which is made up of the matrix material of length, $L_m$, and the rigid reinforcing material of length, $L_r$, has been displayed in Figure 2. It can be indicated that the volume fraction of the reinforcement, $V_f$, in Figure 2, is given by:

$$V_f = 1 - \frac{L_m}{L} \qquad (1)$$

which in general, $V_f$ is less than 1.

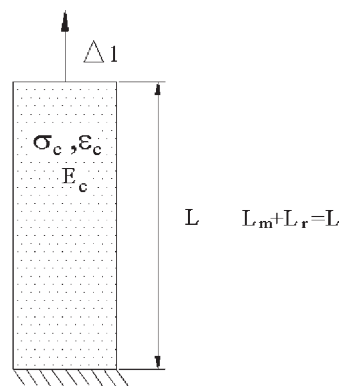


**Figure 1** A homogenized PRMMC material rod, with length *L*.

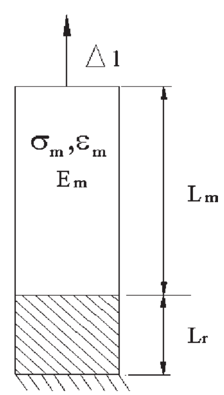


**Figure 2** A PRMMC material rod made up of matrix material of length, $L_m$, and rigid reinforcing material of length, $L_r$.

When both such the composite's rods are subjected to a small displacement, $\Delta l$, the elastic strains and stresses in both rods are given in Eqs. (2) and (3) respectively,

$$\varepsilon_c = \frac{\Delta l}{L}, \qquad \sigma_c = E_c \cdot \varepsilon_c \tag{2}$$

$$\varepsilon_m = \frac{\Delta l}{L_m}, \qquad \sigma_m = E_m \cdot \varepsilon_m \tag{3}$$

where ε, σ, and $E$ are the elastic strain, the elastic stress, and the modulus of elasticity, respectively. The subscript $c$ and $m$ mean the PRMMC material and the corresponding matrix material.

In the present work, it is assumed that the elastic strain energy for the two rods is the same, hence,

$$\sigma_c \cdot \varepsilon_c = \sigma_m \cdot \varepsilon_m . \tag{4}$$

Substituting Eq. (2) and Eq. (3) into Eq. (4), it can be shown that,

$$E_c \cdot \left(\frac{\Delta l}{L}\right)^2 = E_m \cdot \left(\frac{\Delta l}{L_m}\right)^2 . \tag{5}$$

By application of Eq. (1) into Eq. (5), together with adjusting some terms, the form of relationship for the case of modulus of elasticity is

$$E_c = \frac{E_m}{(1-V_f)^2} . \tag{6}$$

Assuming that both the composite material's rods above behave like a rigid-perfectly plastic, then Eq. (4) can be modified and rewritten as:

$$\left(\sigma_y\right)_c \cdot \varepsilon_c = \left(\sigma_y\right)_m \cdot \varepsilon_m . \tag{7}$$

where $\left(\sigma_y\right)_c$ and $\left(\sigma_y\right)_m$ are the yield stress of the PRMMC and the matrix material, respectively.

Substitution of $\varepsilon_c$ and $\varepsilon_m$ from Eq. (2) and Eq. (3) into Eq. (7), with the aid of Eq. (1), the form of relationship for the case of yield stress can be represented as:

$$\left(\sigma_y\right)_c = \frac{\left(\sigma_y\right)_m}{(1-V_f)} . \tag{8}$$

**The tested composite material**

The composite material considered in the current study is an Al-SiC PRMMC. The matrix material is an aluminium alloy, AA6061, and the reinforcement SiC particles. The composite material's tensile stress-strain curves measured experimentally at room temperature for four volume fractions of reinforcement: 15%, 20%, 30% and 40%, as presented in McDanels (1985), are employed in the present work for comparisons. The necessary of both the aluminium alloy matrix and the reinforcement properties data, such as the modulus of elasticity, Poisson ratio, yield tensile strength and density, are shown in Table 1 (McDanels, 1985; Meijer *et al.*, 1997; Aradhya and Surappa, 1991), as well.

**Table 1** Necessarily physical and mechanical properties recorded from experimental investigations on both a matrix alloy (AA6061) and a particulate reinforcement (SiC) at room temperature.

| Material | Mechanical and physical properties | | | |
|---|---|---|---|---|
| | Modulus of elasticity; GPa | Poisson ratio | Yield tensile strength, 0.2% offset; MPa | Density; $Mg/m^3$ |
| AA6061 | 70 | 0.33 | 320 | 2.7 |
| SiC | 429 | 0.17 | - | 3.2 |

## RESULTS AND DISCUSSIONS

**Dependence of the PRMMC's modulus of elasticity on its reinforcement volume fraction**

The results obtained for the modulus of elasticity of AA6061/SiCp over a range of reinforcement volume fraction (from 10% to 40%) made by Eq. (6) are plotted in Figure 3, using the modulus of elasticity of the unreinforced matrix material used in the present work. Also plotted in Figure 3 are the experimental values of the modulus of elasticity of the chosen PRMMC material from McDanels (1985). It can be seen that the predictions tend to overestimate the experimental data in the whole region. In addition, the discrepancy between the data from both resources above increases rapidly, especially beyond 20% volume fraction of reinforcement. Thus, the energy approach predictions evaluated by Eq. (6) seem to provide a poor representation of testing data over the range of reinforcement volume fraction.

However, it is informative to compare the predictions made by Eq. (6) with those made by other techniques. For this purpose, the micromechanical finite element (FE) analyses through using the unit cell approach, developed in the previous work of the author (Suranuntchai, 2002a), is considered. This FE unit cell model allows the nominal stress-strain curves for the PRMMC material consisting of rigid and spherical reinforcing particles embedded in an isotropic matrix material undergoing tensile deformation at a range of volume fraction of reinforcement to be calculated and drawn by Suranuntchai (2002b). From each FE predicted curve corresponding to one reinforcement volume fraction from the unit cell model, the value of the modulus of elasticity of the PRMMC material can be obtained. For simplicity, only the unit cell from simple cubic packing as an idealisation of real composites is carried out in the present project. The 3-D FE mesh, employed to discretize the unit cell, is composed of 8-noded linear brick elements with 2×2×2 Guassian quadrature in each element. Due to the rigid particulate assumption, it is clear that the FE discretization is required only in the matrix. With the help of employing the FE commercial analyzing tool named ABAQUS, the modulus of elasticity values for such the composite predicted by the FE unit cell approach are also included in Figure 3. It can be observed that even there is a noticeable difference between Eq. (6) predictions and the FE

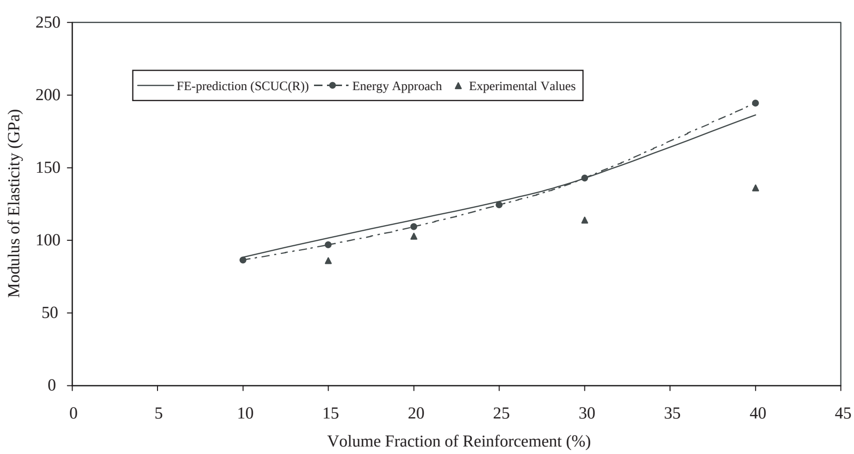


**Figure 3** Graph of modulus of elasticity against volume fraction of reinforcement, showing the approximating values computed by the energy approach (Eq. 6) proposed in the present work, the experimental data, and the FE unit cell predicted curves.

predicted values, but a good and favorable agreement is accepted over the range of reinforcement volume fraction considered.

**Dependence of the PRMMC's yield stress on its reinforcement volume fraction**

As in the case of modulus of elasticity, a simple relationship between the yield stress of the PRMMC material and the unreinforced matrix material and the volume fraction of reinforcement is established using the energy approach, but assuming rigid-perfectly plastic deformation behavior for the matrix material. For avoiding the recapitulation, the form of such relationship adopted can be found in Eq. (8). The predictions made by Eq. (8), employing the unreinforced matrix material's yield stress used in the present work, are plotted in Figure 4. Also plotted on the same graph are the data points obtained from the experimental curves for an AA6061 matrix reinforced with SiC particulate at 15%, 20%, 30% and 40% volume fraction of reinforcement given in McDanels (1985). The correlation between the two sets of data is relatively poor. Similar to the case of modulus of elasticity, the yield stress values predicted by Eq. (8) tend to overestimate the experimental data over a range of reinforcement volume fractions.

Since the yield point for the composite is subjected to definition, thus different definitions may result in different yield stresses for the same material. For the ease of use in the current comparisons, the yield stresses of the PRMMC are taken from that of a rigid perfectly plastic counterpart of the stress-strain curves, which are predicted by the FE unit cell approach. The yield stress values as determined in this way over a range of reinforcement volume fractions are presented in Figure 4, as well. Obviously, the results show an increase in the yield stress of the PRMMC material with increasing volume fraction of reinforcement. In Figure 4, it can also be observed that the results obtained from the FE predictions are relatively better approximation to the experimental data than those obtained from the yield stress variation computed by Eq. (8).

## CONCLUSIONS

In this research paper, the full establishment of simple relationships in order to determine approximately the effective mechanical properties, especially in elastic regime, such as the modulus of elasticity and the yield stress of particulate-reinforced metal matrix composites (PRMMCs) based on the energy approach is concerned. These

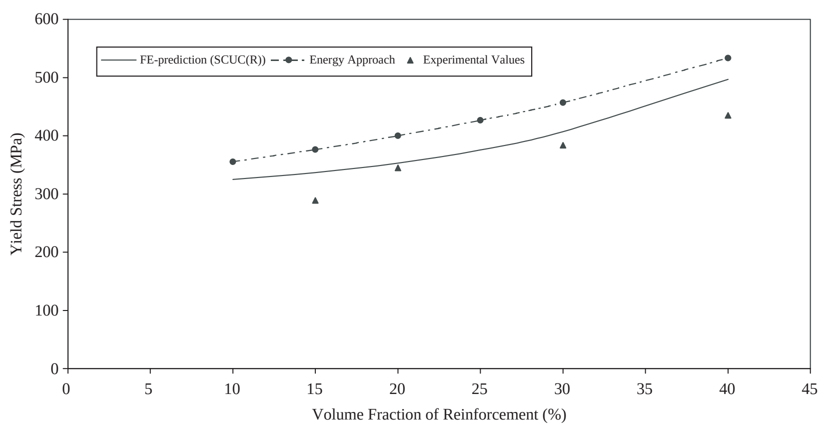


**Figure 4** Graph of yield stress against volume fraction of reinforcement, showing the approximating values computed by the energy approach (Eq. 8) proposed in the present work, the experimental data, and the FE unit cell predicted curves.

relationships enable such the mechanical properties of an aluminium alloy matrix, AA6061, reinforced by SiC particles to be predicted, provided the corresponding properties of the unreinforced matrix material and the reinforcement volume fractions (from™10% to 40%, in the current study) are known.

For the case of modulus of elasticity, the predictions made by such the relationship adopted in the present work agree well with the modulus of elasticity variation obtained from the nominal stress-strain curves that are predicted by the finite element (FE) cubic unit cell approach. However, they seem to provide a poor approximation to the experimental data over a range of volume fractions of reinforcement considered. Similarly, the yield stress values of the chosen PRMMC material evaluated by such the energy approach are apparently closer to the FE predictions than the experiments.

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