Transactions of the Materials Research Society of Japan 24 [2] 141-144 (1999)

The influence of particle size on yield strength of metal matrix composites

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Abstract Influence of particle size on yield strength of particulate reinforced metal matrix composites has been analysis by using strengthening models and the related modification. Experimental data from previous reports were introduced as examination of theoretical analysis. The difference in thermal expansion of particle and matrix resulted in the most significant enhance effect on strength of composites. Generally, when the reinforcement is beyond a critical size, influence of particle size on yield strength of PMMCs became unremarkable.

Keywords particle size, metal matrix composites, yield strength, strengthening models

1 Introduction

The relationship between microstructure and mechanical properties has been built up based on experimental results in PMMCs systems. Some simple and practical relations were used to predict the mechanical behaviors of the composite materials, for example, rule of mixture and related corrections [1,2]. Recently, more detail analysis of effects of microstructure parameters on mechanical properties of PMMCs has been developed [3-9]. However, systematic information on effects of particle size on strength of PMMCs is very little and the exact role of reinforcement size is still unrealized. Theoretically, this is reflected by the general disagreement in predictions and published findings [8-10]. In practice, there exits an experimental point of view considered that in PMMCs fabrication, the finer the particle is, the higher the strength can be obtained. Thus, to reduce the reinforcement size seems to be very important when expected the material with high strength, especially in an in-situ system. Virtually how much strength can be gained at the expense of increased cost and processing complexity is unclear.

In fact, all models regarding the strengthening effects of particulate reinforcements predict that yield strength of composites is increased compared with that of the matrix, although there are some contrary experimental reports [11,12]. Generally, the strengthening effect of particle is attributed to two factors:

(1) load bearing feature of the hard particles [9, 13, 14]
(2) the model associated with increasing in dislocation density of matrix [15,16], such as Orowan process [17], quench strengthening mechanism [18] and effect of work hardening process [19,20].

Of course, strength increased by improvement in matrix structure, such as Hall-Petch relation should be considered. In the absence of fully developed theories to predict the yield strength of PMMCs with varying volume fraction and particle size, it is possible to utilize these existing models to estimate the various contribution of particle to the yield strength. These models have been used to predict the yield strength of composites and to compare with the experimental data in some pervious work [17, 19, 21, 22], although the complex interactions between the various mechanisms have not been considered.

The present study has used the aforementioned models to reveal the influence of particle size on yield strength of PMMCs, and used the experimental data from wide sources to examine the analysis. Interaction between model (1) and (2) has also been considered.

2 Strengthening mechanisms and related modification

2.1 For an equiaxed particle, an increase in yield strength due to load transfer $\Delta\sigma_{Trans}$ can be expressed as:

$$\Delta\sigma_{Trans} = \sigma_m(0.5f) \quad (1)$$

where σ_m is yield stress of matrix and f is volume fraction.

2.2 The increase of yield strength due to Orowan process $\Delta\sigma_O$ can be expressed as:

$$\Delta\sigma_O = Gb(2\pi/f)^{-1/2}/3d \quad (2)$$

where G is the elastic shear modulus of the matrix, b is the Burgers vector of matrix metal, and d is the particle size.

2.3 An increase of yield strength due to dislocation generation by a difference in thermal expansion $\Delta\sigma_{CTE}$ can be expressed as:

$$\Delta\sigma_{CTE} = \beta Gb(12\Delta T\Delta Cf/bd)^{1/2} \quad (3)$$

where β is a constant, between 0.5 and 1.25 [19], ΔT is the temperature change during cooling, and ΔC is the difference in thermal expansion coefficients between matrix and particle.

2.4 The increase of yield strength associated with work hardening process $\Delta\sigma_{WH}$ can be expressed as:

$$\Delta\sigma_{WH} = \alpha Gb(f8\gamma/bd)^{1/2} \quad (4)$$

where α is a constant of the order of 1 [6], and γ is the shear strain calculated as 0.0131 from [22].

2.5 Hall-Petch relation in matrix leads to the familiar expression of $\Delta\sigma_{HP}$:

$$\Delta\sigma_{HP} = K(d_c^{-1/2} - d_m^{-1/2}) \quad (5)$$

where K is a constant, and d_c, d_m is the mean grain size of composite and unreinforced alloy respectively.

2.6 N. Ramakrishnan proposed the yield strength of composites σ_c can be expressed as [7]:

$$\sigma_c = \sigma_m(1+f_d)(1+f_l) \quad (6)$$

where f_d and f_t represent the influence factor of dislocation density and load transfer mechanism respectively.

$$f_d = (kGb\rho^{1/2})/\sigma_m \quad (7)$$

$$f_t = 0.5f \quad (8)$$

where k is a constant (≅1.25), and ρ is the dislocation density which can be expressed as [19]:

$$\rho = 12\Delta T\Delta Cf/bd \quad (9)$$

From equation (6), the additional increase in yield strength due to interaction of f_d and f_t $\Delta\sigma_{Inter}$ is:

$$\Delta\sigma_{Inter} = \sigma_m f_d f_t \quad (10)$$

Combining equation (7)-(10) we get,

$$\Delta\sigma_{Inter} = 0.5kGf^{3/2}(12\Delta T\Delta Cb/d)^{1/2} \quad (11)$$

Among these equations, increase of yield strength of the composites was related to reinforcement size in equations (2), (3), (4) and (11). One can calculated these mechanisms in Al/SiC$_p$ system by using parameters listed in table 1. Fig. 1 shows the increase of yield strength as a function of particle size in each mechanism. All models show similar character. In a wide range of particle size, enhancement of yield strength shows no much difference. Influence of particle size becomes significant when the particle is small, normally less than 0.5μm in Orowan and work hardening mechanism, while less than 20μm in mechanisms shown in fig. 1 (b) and (d). There always exits a critical particle size beyond which the enhance effect almost disappeared. With increase volume fraction of particulate reinforcement, the critical particle size increased in all mechanisms. According to fig. 1, among all enhance influence to yield strength, $\Delta\sigma_{CTE}$ induced by dislocation generation by a difference in thermal expansion shows the most significant effect.

Considering the overall influence of particle size on yield strength of composites, fig. 2 can be obtained by piling up of mechanisms in fig. 1. The present prediction resulted in considerably higher yield strength in composite materials with models without adding $\Delta\sigma_{Inter}$. Experimental data from previous reports [23-30] were also plotted in this figure. These data compared basically favorite with theoretical analysis according to fig. 2, although they are generally lower than that of the predictions. This is mainly because in theoretical analysis ideal models were supposed based on hypotheses such as homogenous distribution and free from defects. And these hypotheses can not be satisfied in practical fabrication of PMMCs, especially when particle size is fine.

Adding the enhance influence in equations (1) to (5) and (11), we get:

$$\sigma_c(d,f) = \Delta\sigma_{Trans} + \Delta\sigma_O + \Delta\sigma_{CTE} + \Delta\sigma_{HP} + \Delta\sigma_{WH} + \Delta\sigma_{Inter} \quad (12)$$

Then, $\partial\sigma_c/\partial d$ can be calculated (fig. 3). From fig. 3 one can clearly observed the exact influence of particle size on yield strength of composites. When particle size is larger than 5μm, influence of particle size on yield strength of PMMCs became unremarkable.

Table 1 Summary of parameters used for calculation

α	b (nm)	G (GPa)	β	ΔT (℃)	ΔC ($\times 10^{-6}$/℃)	K	γ
1	0.283	70	1.25	600	19.3	1.25	0.0131

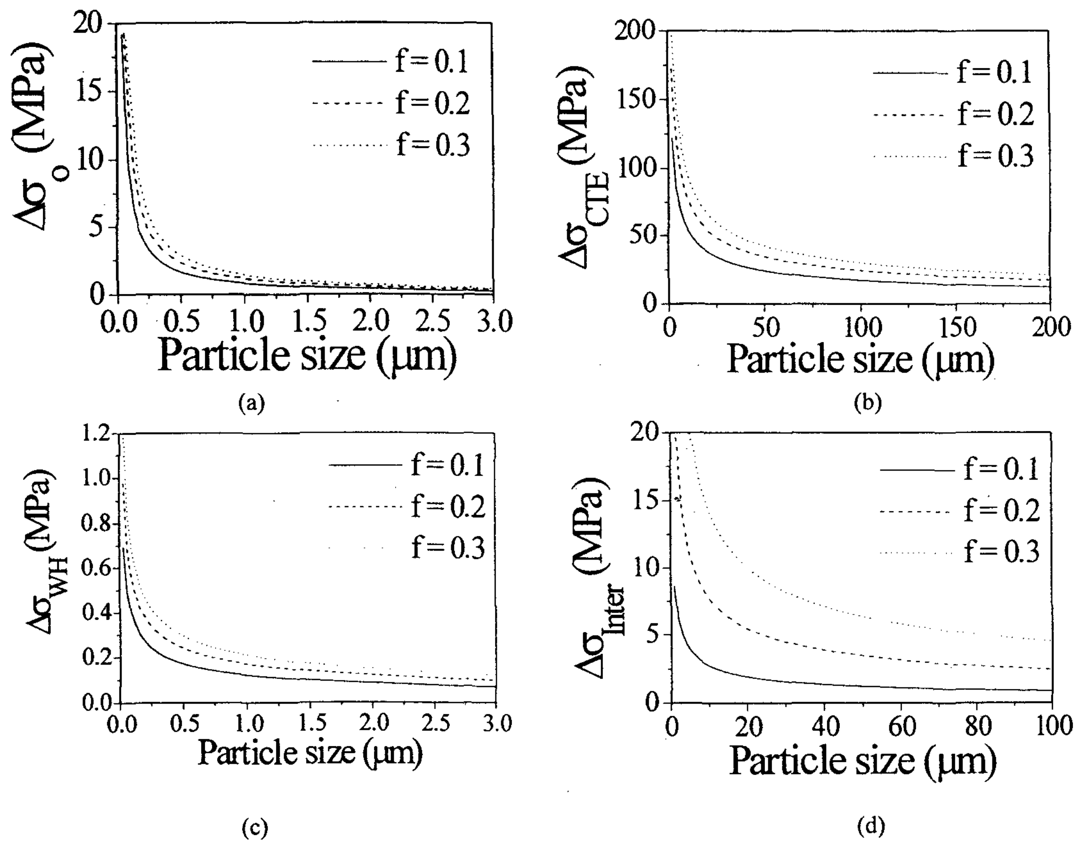

Fig. 1 Yield strength increased as a function of particle size due to (a) Orowan process, (b) difference in thermal expansion, (c) effect of work hardening and (d) interaction of the influence of dislocation density and load transfer mechanism

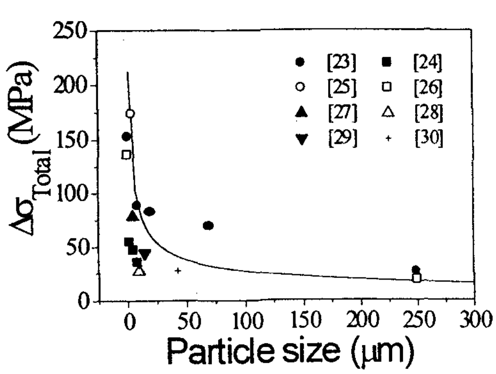

Fig. 2 Total yield strength increased as a function of particle size due to particle reinforcement and experimental data from previous works (f = 0.2)

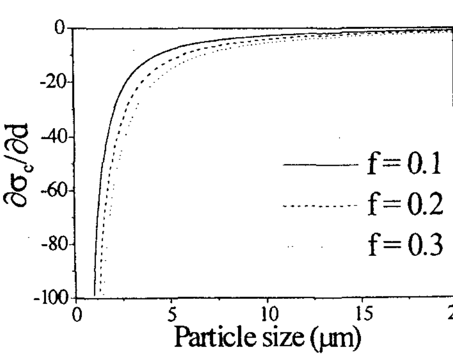

Fig. 3 Changing rate of σ_c ($\partial\sigma_c / \partial d$) as a function of particle size

3 Summary

In all models the difference in thermal expansion of particle and matrix resulted in the most significant enhance effect on yield strength of the composites. There exits a critical size beyond which particle size shows little influence on yield strength. Critical size was less than 0.5μm in Orowan and work hardening mechanisms and less than 20μm in thermal expansion and interaction mechanisms. Generally, when particle size is larger than 5μm, influence of particle size on yield strength of PMMCs became unremarkable.

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