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Strengthening mechanisms based on reinforcement distribution uniformity for particle reinforced aluminum matrix composites

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Abstract: A modified mixed strengthening model was proposed for describing the yield strength of particle reinforced aluminum matrix composites. The strengthening mechanisms of the composites were analyzed based on the microstructures and compression mechanical properties. The distribution uniformity of reinforcements and cooperation relationship among dislocation mechanisms were considered in the modified mixed strengthening model by introducing a distribution uniformity factor u and a cooperation coefficient f_c, respectively. The results show that the modified mixed strengthening model can accurately describe the yield strengths of Al_3Ti/2024 Al composites with a relative deviation less than 1.2%, which is much more accurate than other strengthening models. The modified mixed model can also be used to predict the yield strength of Al_3Ti/2024 Al composites with different fractions of reinforcements.

Key words: metal matrix composite; strengthening model; yield strength; reinforcement; distribution uniformity

1 Introduction

Particle reinforced metal matrix composites (PRMMCs) have been widely used in aerospace and ordnance industries due to their excellent properties, e.g. high specific strength and stiffness [1−3]. Understanding the strengthening mechanisms and hence predicting the yield strength are not only important for fabricating high performance metal matrix composites, but also crucial for producing high quality components. Much work has been done to clarify strengthening mechanisms of PRMMCs in the past few decades [4−6]. Some mechanisms, e.g. load transfer from matrix to particles, thermal mismatch strengthening, Hall−Petch strengthening, Orowan strengthening and work hardening, have been acknowledged to be responsible for the high mechanical strength of PRMMCs.

In order to accurately describe the yield strength of PRMMCs, a numerical model integrating relevant strengthening mechanisms should be established, e.g. mixed strengthening model [7], Ramakrishnan model [8], and Eshelby model [9]. However, a certain deviation always exists between the calculated value and experimental data, which can be attributed to two reasons: (1) the distribution uniformity of particle reinforcements has a significant effect on the mechanical properties; (2) there is a cooperation relationship among different strengthening mechanisms, and it should be considered in the numerical model.

To the best of our knowledge, although much work has been done on strengthening mechanisms of metal matrix composites, limited work has been reported on the effects of particle distribution uniformity and cooperation relationship among different strengthening mechanisms on the strengthening model of PRMMCs.

In this work, aluminum matrix composites reinforced with in-situ Al_3Ti particles were fabricated by ultrasonic vibration followed by squeeze casting. The particle distribution uniformity was calculated. A strengthening model based on the particle distribution uniformity and the cooperation relationship among

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dislocation mechanisms was established. The results will be beneficial to accurately describing the yield strength and promoting the industrial application of particle reinforced metal matrix composites.

2 Experimental

Pure Ti powders (99.7% purity) with an average diameter of 20 μm and 2024 Al alloy ingots were adopted as reagent and metal matrix, respectively. The 2024 Al alloy was melted in a graphite crucible by an induction heater at 785 °C, and then the Ti powders wrapped with Al foil were added into the Al melt. Subsequently, the melt was treated by ultrasonic vibration (with a power of 1.8 kW and a frequency of 20 kHz) for 15 min. After ultrasonic treatment, the melt was rapidly poured into squeeze casting dies which were preheated to 350 °C, and solidified under a pressure of 150 MPa. 2024 Al matrix composite ingots reinforced by Al_3Ti particles with different contents (mass fraction, %) were prepared [10], and then subjected to a T6 heat treatment (solution treatment at 500 °C for 6 h followed by water quenching and then aging at 180 °C for 4 h).

Samples with a diameter of 10 mm and a height of 12 mm were cut from the ingots for microstructure examination, and prepared by standard metallographic technique of grinding with SiC abrasive and polishing with a diamond spray (0.5 mm). The microstructures were examined by scanning electron microscopy (SEM). Grain/particle size $D(=(4A/\pi)^{1/2}$, A is the area of solid grain/particle) and shape factor $F(=4\pi A/P^2$, P is the particle perimeter) were measured from resulting microstructures using an image analysis system [11−13]. Compression samples were taken from the transverse section of the ingots by electrospark wire-electrode cutting method. The compression mechanical properties were measured using an Instron 5569 testing machine at a crosshead speed of 1 mm/min. Each compression value is the average of at least three measurements.

3 Results and discussion

3.1 Microstructures

Figure 1 shows the backscattered electron micrographs of Al_3Ti/2024 Al composites with different mass fractions of Al_3Ti particles. When the mass fraction of reinforcements is 4%, some of the Al_3Ti particles are agglomerated (indicated by the red dashed circles in Fig. 1(a)). As the mass fraction of reinforcements increases, most of the Al_3Ti particles are evenly distributed in the α(Al) matrix (Figs. 1(b)−(d)). The distribution of Al_3Ti particles seems to be increasingly uniform as their mass fraction increases.

In order to evaluate the distribution uniformity of Al_3Ti particles, a region with dimensions of 500 μm × 500 μm was taken from the SEM micrograph, and then it was divided into 100 parts with dimensions of 50 μm × 50 μm. Subsequently, the amount of Al_3Ti particles in each part was counted. Therefore, the average amount of Al_3Ti particles in a part ($\overline{P}$) can be calculated according

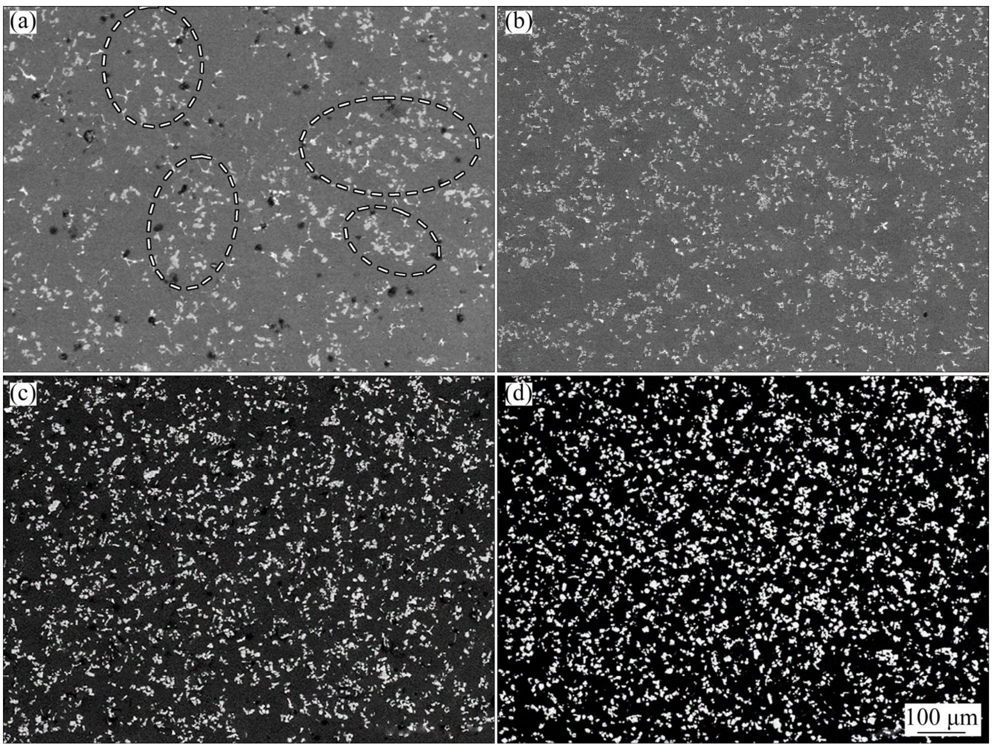

Fig. 1 Backscattered electron micrographs of Al_3Ti/2024 Al composites with different mass fractions of reinforcements: (a) 4%; (b) 8%; (c) 12%; (d) 16%

to Eq. (1). The distribution uniformity of Al_3Ti particles in α(Al) matrix can be calculated by Eq. (2).

$$\overline{P}=\frac{1}{N}\sum_{i=1}^{N}P_i \tag{1}$$

$$u=1-\sum_{i=1}^{N}\frac{|P_i-\overline{P}|}{N\overline{P}} \tag{2}$$

where P_i is the amount of Al_3Ti particles in unit i, N is the total unit numbers, and u is the distribution uniformity factor of reinforcements. The maximum value of u being 1 indicates that the distribution is perfectly uniform. Larger u value indicates that the distribution of particles is more uniform.

Figure 2 shows the distribution uniformity factor and average size of reinforcements in Al_3Ti/2024 Al composites. As shown in Fig. 2, the distribution uniformity and average size of Al_3Ti particles both increase as the mass fraction increases. When the mass fractions of reinforcements are 4%, 8%, 12% and 16%, the distribution uniformity factors of Al_3Ti particles are 0.65, 0.84, 0.88 and 0.89, respectively, and the average particle sizes are 6.4, 6.7, 7.5 and 8.6 μm, respectively.

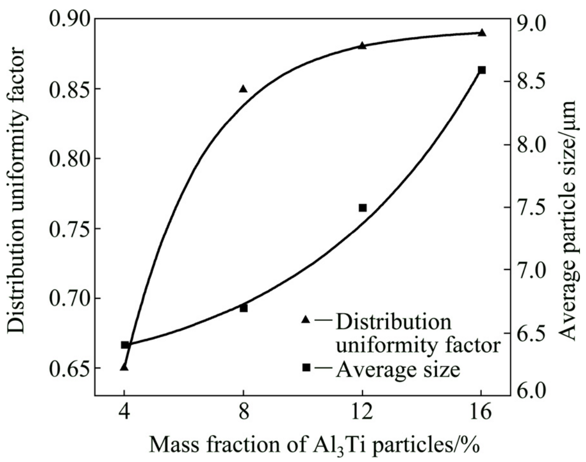

Fig. 2 Distribution uniformity factor and average size of reinforcements in Al_3Ti/2024 Al composites

3.2 Mechanical properties

Figure 3 shows the yield strength of Al_3Ti/2024 Al composites. Compared with 2024 Al alloy, the yield strengths of composites are improved evidently. When the mass fraction of reinforcements is increased from 4% to 16%, the yield strength is improved from 334 to 390 MPa.

As indicated in Fig. 3, the mechanical properties can be significantly improved by adding reinforcements in the Al matrix. Besides the content of reinforcing particles, the distribution uniformity of reinforcements also has significant effect on the mechanical performance of metal matrix composites. However, most of the strengthening models are established by assuming the condition that the distribution of reinforcements is perfectly uniform. The schematic diagram of particle distribution is shown in Fig. 4. In a micro-area, one part region (the upper part) is reinforced by the particles while the other region (the bottom part) is not reinforced and could still be regarded as Al matrix. The yield strength of particle-reinforced region can be calculated by $\sigma_{my}+\Delta\sigma$ (σ_{my} is the yield strength of matrix). Therefore, the yield strength of the composites σ_c can be calculated according to a modified mixed model:

$$\sigma_c=u(\sigma_{my}+\Delta\sigma)+(1-u)\sigma_{my}=\sigma_{my}+u\Delta\sigma \tag{3}$$

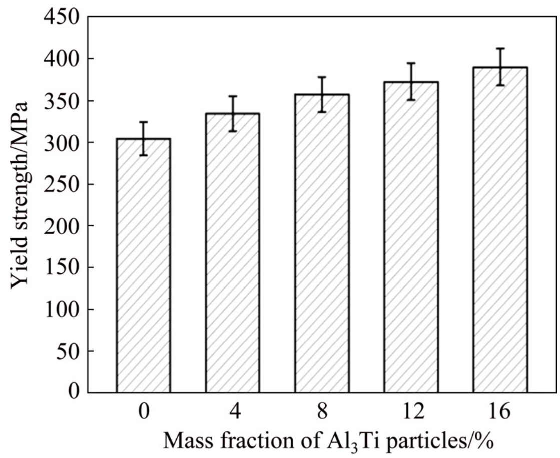

Fig. 3 Yield strength of Al_3Ti/2024 Al composites

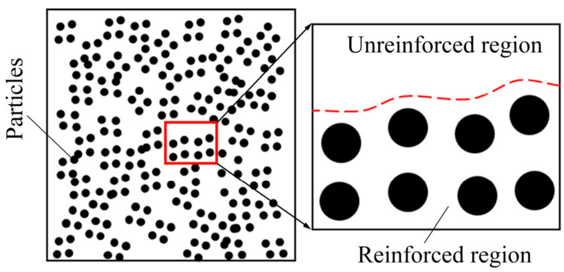

Fig. 4 Schematic diagram of particles distribution in matrix

3.3 Strengthening model

The strength increment $\Delta\sigma$ is based on the combined effects of various strengthening mechanisms, such as the thermal mismatch strengthening, the Hall−Petch strengthening, the work hardening and the load transfer strengthening. When calculating the yield strength of composites, the volume fraction of reinforcements (f_v) is usually adopted, which can be calculated by the following equation:

$$f_v=\frac{f_m/\rho_{Al_3Ti}}{f_m/\rho_{Al_3Ti}+(1-f_m)\rho_{2024}}\times 100\% \tag{4}$$

where f_m is the mass fraction of reinforcements, ρ_{Al_3Ti} is the density of Al_3Ti phase, and ρ_{2024} is the density of 2024 alloy.

Thermal mismatch strengthening is attributed to the difference of thermal expansion coefficients between the reinforcements and the matrix [2]. When the temperature changes, the volume variations of reinforcements and matrix are different, resulting in a deformation occurring in the matrix adjacent to the reinforcements. Therefore, the dislocation density is increased, which is beneficial to improving the mechanical properties, as indicated by the transmission electron micrograph of 16% Al_3Ti/2024 Al composite in Fig. 5. The strengthening effect ($\Delta\sigma_{CTE}$, ρ) can be calculated according to the following equations [14]:

$$\Delta\sigma_{CTE} = kG_m b\sqrt{\rho} \tag{5}$$

$$\rho = \frac{12\Delta T \Delta\alpha f'_v}{(1-f'_v)bd} \tag{6}$$

where k is a constant between 0.5 and 1, G_m is the shear modulus of matrix (28.0 GPa for 2024 Al alloy), b is the value of Burgers vector of matrix (5.73×10^{-10} m for 2024 Al alloy), ΔT is the difference between the solution and room temperatures (480 K), $\Delta\alpha$ is the difference of thermal expansion coefficients between matrix and reinforcements (13×10^{-6} K^{-1}), d is the average diameter of particles (μm), and f'_v is the relative volume fraction, which can be calculated according to $f'_v=f_v/u$.

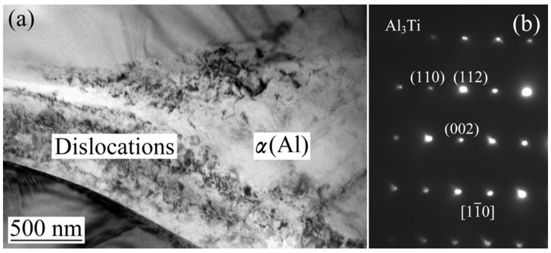

Fig. 5 TEM image of 16% Al_3Ti/2024 Al composite (a) and diffraction patterns of Al_2Ti (b)

Hall−Petch strengthening is based on the grain refinement of the matrix, and it can be calculated according to the following equation [15]:

$$\Delta\sigma_{grain} = K_y\left(D^{-1/2} - D_0^{-1/2}\right) \tag{7}$$

where K_y is a constant which is related to grain boundary structures (74 MPa·$\mu m^{1/2}$), D is the average grain size of composite, and D_0 is the average grain size of 2024 Al alloy.

Work hardening is based on the interaction between the reinforcement and the matrix during the deformation process, which is a unique strengthening mechanism for metal matrix composites [6]. The strengthening effect includes two parts: (1) the dislocation motion is inhibited by the interface between the matrix and the reinforcement, leading to an increase in yield strength ($\Delta\sigma_{wh1}$); (2) stress relaxation of Orowan ring is caused by the interface stress between the matrix and the reinforcement in a low strain region, so a deformation occurs in the matrix adjacent to the interface in order to satisfy the continuity of materials, also leading to an increase in yield strength ($\Delta\sigma_{wh2}$). The work hardening effect can be calculated according to the following equations [16]:

$$\Delta\sigma_{wh1} = 4.5Gf'_v\varepsilon \tag{8}$$

$$\Delta\sigma_{wh2} = 5G\sqrt{2f'_v b\varepsilon/d} \tag{9}$$

where ε is the true strain.

The thermal mismatch strengthening, Hall−Petch strengthening and work hardening are all based on dislocation strengthening mechanism. Therefore, these mechanisms should not be independent. A cooperation coefficient f_c was defined to describe the cooperation relationship among dislocation mechanisms. The dislocation strengthening effect can be calculated according to the following equation:

$$\Delta\sigma_{dislocation}=f_c(\Delta\sigma_{CTE}+\Delta\sigma_{grain}+\Delta\sigma_{wh1}+\Delta\sigma_{wh2}) \tag{10}$$

For the load transfer strengthening mechanism, NARDONE and PREWO [17] proposed a modified shear lag model, which considered the principal tensile stress and shear stress subjected by the reinforcements during the load transfer process. The load transfer strengthening effect can be calculated according to the following equation:

$$\Delta\sigma_{transfer} = \frac{1}{2}\sigma'_{my}f'_v = \frac{1}{2}(\sigma_{my}+\sigma_{dislocation})f'_v \tag{11}$$

where σ'_{my} is the yield strength of matrix which considered the strengthening effect of dislocation. The calculated results of each strengthening effect are listed in Table 1.

Table 1 Calculated results of every strengthening effect of Al_3Ti/2024 Al composites

Mass fraction of Al_3Ti particles/%	$\Delta\sigma_{dislocation}$				$\Delta\sigma_{transfer}$
	$\Delta\sigma_{CTE}$	$\Delta\sigma_{grain}$	$\Delta\sigma_{wh1}$	$\Delta\sigma_{wh1}$	
4	21.2	2.1	13.1	19.1	9.4
8	26.4	3.3	20.5	23.4	15.4
12	30.1	4.4	28.8	26.2	22.5
16	32.7	5.9	37.5	27.9	30.3

Taking Eqs. (10) and (11) into the modified mixed model (Eq. (4)), the yield strength of composites can be calculated:

$$\sigma_c = \sigma_{my} + u[f_c(\Delta\sigma_{CTE} + \Delta\sigma_{grain} + \Delta\sigma_{wh1} + \Delta\sigma_{wh2}) + \frac{1}{2}\sigma'_{my}f'_v] \tag{12}$$

By comparing the calculated results with experimental values, the cooperation coefficient f_c of

Al_3Ti/2024 Al composites can be determined to be 0.664. Figure 6 shows the comparison of calculated yield strengths based on different strengthening models and experimental values. As indicated in Fig. 6, the modified mixed model, which considered the distribution uniformity of the reinforcements and the cooperation relationship among dislocation mechanisms, can accurately describe the yield strengths of Al_3Ti/2024 Al composites. Table 2 shows the relative deviations of different strengthening models. The relative deviation of modified mixed model in this work is the smallest (less than 1.2%), indicating that the modified mixed model is much more accurate than other strengthening models in describing the mechanical properties. Furthermore, the modified mixed model can also be used to predict the yield strength of Al_3Ti/2024 Al composites with different mass fractions of reinforcements.

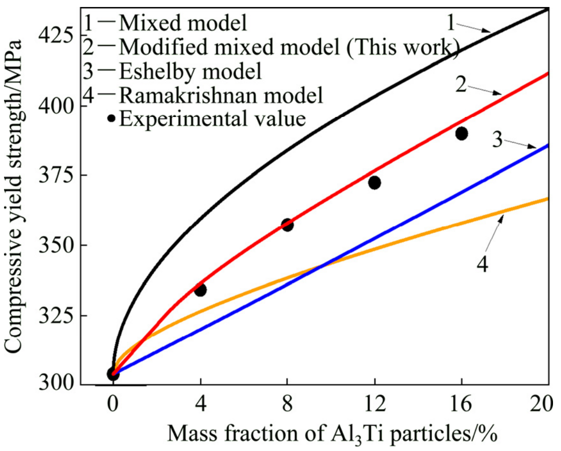

Fig. 6 Comparison of calculated yield strengths based on different strengthening models and experimental values

Table 2 Relative deviations of different strengthening models

Mass fraction of Al_3Ti particles/%	Relative deviation/%			
	Mixed model	Ramakrishnan model	Eshelby model	This work
4	7.56	2.32	4.25	0.65
8	7.48	5.29	5.93	0.17
12	8.27	6.42	5.38	1.12
16	7.64	8.21	5.37	1.12

4 Conclusions

1) A distribution uniformity factor u was defined to indicate the distribution uniformity of reinforcements. When the mass fractions of the reinforcements are 4%, 8%, 12% and 16%, the distribution uniformity factors of Al_3Ti particles are 0.65, 0.84, 0.88 and 0.89, respectively.

2) A cooperation coefficient f_c was defined to quantify the cooperation relationship among different strengthening mechanisms, e.g. the thermal mismatch strengthening, Hall−Petch strengthening and work hardening. The cooperation coefficient f_c of Al_3Ti/2024 Al composites was determined to be 0.664.

3) The modified mixed strengthening model can accurately describe the yield strengths of Al_3Ti/2024 Al composites with a relative deviation less than 1.2%.

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基于增强相分布均匀性的颗粒增强铝基复合材料的强化机制

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摘　要：提出一种用于描述颗粒增强铝基复合材料屈服强度的综合强化模型。基于复合材料显微组织及压缩力学性能检测，对铝基复合材料的强化机制进行研究。为了精确地描述增强相分布均匀性和不同位错强化机制间的协同关系对强化效果的影响，在综合强化模型中引入颗粒分布均匀性因子 u 和协同系数 f_c。结果表明，本研究提出的综合强化模型预测结果与实验结果吻合很好，可以精确地描述 Al_3Ti/2024 Al 复合材料的屈服强度，理论与实验误差小于 1.2%，其预测精度远高于现有综合强化模型的预测精度。该模型也可适用于预测具有不同比例增强相的 Al_3Ti/2024 Al 复合材料的屈服强度。

关键词：金属基复合材料；强化模型；屈服强度；增强相；分布均匀性

(Edited by Wei-ping CHEN)