TENSILE STRENGTH ANALYSIS ON δ-Al_2O_3 SHORT FIBER REINFORCED Al-12Si ALLOY COMPOSITES①

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ABSTRACT Al-12Si, Al-12Si-Cu and Al-12Si-Mg matrix composites reinforced with δ-Al_2O_3 short fibres were fabricated by using squeeze-casting. The three composites' room temperature tensile strengths were analyzed by linear regression method (LRM). Their prediction equations for φ_{min}, φ_c and σ'_m were worked out accurately. The relationship between σ'_m and σ_{um} was discussed in detail. The results showed that the reinforcing effect of composite decreases with increasing σ'_m, and σ'_m and $\frac{\sigma'_m}{\sigma_{um}}$ increase with increasing matrix strength so that the higher the strength of the matrix is, the lower the reinforcing effect of composite is.

Key words metal matrix composite linear regression method (LRM) strength fracture

1 INTRODUCTION

The rule of mixture (ROM) used in metal matrix composites (MMC), especially short fiber reinforced MMCs (SFR MMCs) is still unperfect so far. There are a lot of arguements about C_0, σ'_m and τ_i [1-4]. These factors must be more accurate, so that ROM can be more perfect. σ'_m is an important factor in strength prediction of SFR MMCs, there are two different arguing view points about it: 1) Baxter[3] thought that on one hand composites usually fail on low strain level, so σ'_m should be lower than σ_{um}, but on the other hand, the addition of fibres to matrix alloy will refine the grain size of matrix and result in high dislocation density in matrix then strengthen matrix, comprehensively σ'_m should equal to σ_{um} approximately; 2) Friend[4] believed that the stress related to 0.67% strain (the fracture strain of "Saffil" fibre) in the stress-strain curve of composite is σ'_m because composite fails when fibre begins to fracture. But the value of σ'_m according to this method is not precise because the failure of SFR MMCs is very complicated in fact. To quantify σ'_m accurately, room temperature tensile strengths of three kinds aluminum alloys (Al-12Si, Al-12Si-Cu and Al-12Si-Mg) matrix composites reinforced with "Saffil" short fiber were analyzed by linear regression method (LRM) in this study, their prediction equations and σ'_m were worked out and σ'_m was discussed in detail.

2 EXPERIMENTAL MATERIALS AND PROCESSING

Matrix alloys chosen in this work were Al-12Si, Al-12Si-Cu, Al-12Si-Mg which were modified by 33.3% NaCl + 66.7% NaF, their compositions were listed in Table 1. Reinforcement was "Saffil" short fiber provided by ICI Corp, its main phase was δ-Al_2O_3. Silica solution was used in preforms as a binder. Composites were preformed by liquid-squeeze-casting method. Tensile specimens were ASTM standard of d 2.9 mm × 25.4 mm. Tensile experi-

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ments were conducted on SHIMADZU tensile testing machine. Stress rate was 2 mm/s.

Table 1 Compositions of matrix alloys(%)

Alloy	Si	Mg	Cu	Fe	Al
Al-12Si	14.08	–	–	Trace	Balance
Al-12Si-Cu	14.92	–	1.00	Trace	Balance
Al-12Si-Mg	13.08	0.93	–	Trace	Balance

3 RESULTS AND DISCUSSION

3.1 Principle of experimental data processing

It is known that σ_c of SFR MMCs is given as[2]:

$$\sigma_c = C_0 \varphi_f \sigma_f [l - l_c/(2\bar{l})] + \sigma_m (l - \varphi_f) \quad \bar{l} > l_c \quad (1)$$

where $l_c = \sigma_f d/(2\tau_i)$

Eqn. 1 is modified from rule of Mixture (ROM) of continuous fibre reinforced composites ($\sigma_c = \sigma_f \varphi_f + \sigma_{um}(1-\varphi_f)$)[5] and it can be changed into

$$\sigma_c = a\varphi_f + b \quad (2)$$

where

$$a = C_0 \sigma_f [1 - l_c/(2\bar{l})] - \sigma'_m \quad (3)$$

$$b = \sigma'_m \quad (4)$$

It can be seen that σ_c is a linear function of φ_f.

So Eqn. 2 can be quantified by LRM when a series of σ_c and φ_f values have been measured:

$$\sigma_c = \bar{a}\varphi_f + \bar{b} \quad (5)$$

where

$$\bar{a} = \sum_{i=1}^{n} (\varphi_{fi} - \bar{\varphi}_f)(\sigma_{ci} - \bar{\sigma}_c) / \sum_{i=1}^{n} (\varphi_{fi} - \bar{\varphi}_f)^2 \quad (6)$$

$$\bar{b} = \bar{\sigma}_c - \bar{a} \cdot \bar{\varphi}_f \quad (7)$$

where $\bar{\sigma}_c$, $\bar{\varphi}_f$ is the mean value of σ_c, φ_f gotten from experiment of a composite.

3.2 Experimental results

The room tensile strengths of the three composites are listed in Table 2.

These values were used in the method discribed above.

(1) For Al-12Si matrix, there is

$$\sigma_c = 624\varphi_f + 191.0 \quad (8)$$

When $\varphi_f = 0$, $\sigma_c = \sigma_m = 191.0$ MPa $< \sigma_{um}$. So, according to the definition of minimum volume fraction φ_{min} and critical volume fraction φ_c [4] (fibre acts as a reinforcing factor but not a impurity to matrix only when $\varphi_f > \varphi_c$), we have

$$\varphi_{min} = \frac{\sigma_{um} - \sigma'_m}{\bar{a} + \sigma_{um}} \quad (9)$$

$$\varphi_c = \frac{\sigma_{um} - \sigma'_m}{\bar{a}} \quad (10)$$

φ_{min} and φ_c in Al-12Si matrix composites are $\varphi_{min} = 5.23\%$, $\varphi_c = 7.21\%$, respectively.

(2) For Al-12Si-Cu matrix, there are

$$\sigma_c = 450\varphi_f + 225.5 \quad (11)$$

$\sigma'_m = 225.5$ MPa $< \sigma_{um}$, $\varphi_{min} = 3.22\%$, $\varphi_c = 5.00\%$.

(3) For Al-12Si-Mg matrix, there exist

$$\sigma_c = 64.2\varphi_f + 305.4 \quad (12)$$

$\sigma'_m = 305.4$ MPa $> \sigma_{um}$, then there are no φ_{min} and φ_c.

3.3 Discussion

Fig. 1 shows the three prediction curves to-

Table 2 Mechanical properties of composites with different volume fractions (φ_i) of reinforcer

φ_f	Al-12Si		Al-12Si-Cu		Al-12Si-Mg	
	σ_c/MPa	δ/%	σ_c/MPa	δ/%	σ_c/MPa	δ/%
0	236	4.04	248	2.84	285	1.64
6	228	2.51	–	–	–	–
10	255	2.84	268	2.41	312	4.52
15	281	1.20	299	1.53	–	–
18	–	–	–	–	316	2.08
20	319	2.35	313	2.05	319	1.88
29	371	1.76	–	–	–	–

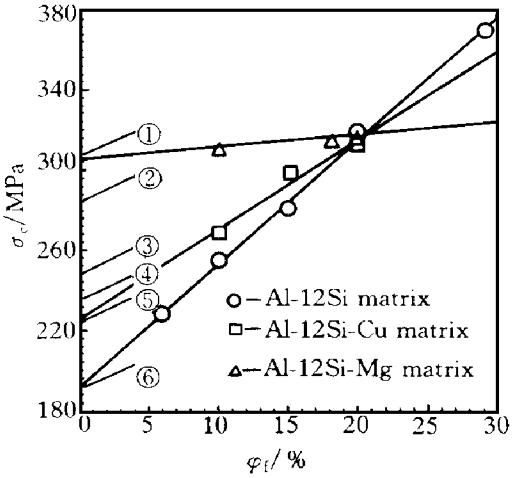

Fig. 1 Comparison of three composites' curves
①—σ'_m (Al-12Si-Mg) = 305.4 MPa;
②—σ_{um}(Al-12Si-Mg) = 285.0 MPa;
③—σ_{um}(Al-12Si-Cu) = 248.0 MPa;
④— σ_{um}(Al-12Si)) = 236.0 MPa;
⑤—σ'_m (Al-12Si-Cu)) = 225.5 MPa;
⑥—σ'_m (Al-12Si) = 191.0 MPa

gether. It can be seen that:

(1) All composites are reinforced by fibres when $\varphi_f > \varphi_c$. σ_c increases with φ_f increasing;

(2) With the addition of Cu or Mg alloy element, Al alloy matrix strength becomes higher;

(3) The slope of the prediction curve (i. e. the reinforcing effect of a composite) increases with matrix strength decreasing.

Al-12Si is an excellent eutectic alloy, so it has good pourability. When it is modificated, it also has good mechanical properties. But it can not be strengthened by solid solution. The addition of Cu or Mg alloy element to Al-12Si can obtain good solid solution effect, and the effect of Mg is better than that of Cu when their additional quantity is equal. So the matrix strength of Al-12Si-Mg is higher than that of Al-12Si-Cu whose strength is higher than that of Al-12Si, but tensile ductility becomes lower and lower. Very brittle fibre's addition refines grain size of matrix alloy, and consequently enhances matrix strength, but it deteriorates ductility of composite deteriorates. Therefore, σ_c increases but δ decreases with φ_f increasing.

From Eqn. 3 it can be seen that:

$$a = C_0\sigma_f[1 - l_c/(2\bar{l})] - \sigma'_m$$

where $l_c = \sigma_f d/(2\tau_i)$

according to shear lag theory, Eqn. 1 is based on the assumption that interfacial bond is perfect and strong enough and interface shear stress is constant. So, when the matrix and reinforcer have been selected, a, the slope of the prediction curve which symbolizes the reinforcing effect of composites, mainly depends on σ'_m and a increases with σ'_m decreasing. Fig. 1 shows this.

σ'_m is the matrix stress when composites fail. If the interfacial bond is strong enough, it can be regarded that the strain of matrix is approximately equal to that of fibre before fibre doesn't fail. Although fibre's fracture strain is far less than unreinforced matrix alloy's, when fibre fractures, σ'_m should be higher than the stress of unreinforced matrix alloy when its strain attains fibre's fracture strain. In SFR MMCs the misfit of the coefficients of thermal expansion between fibre and matrix will result in high thermal stress near interface. Very complicated distribution of fibres also causes non-uniform stress distribution in the matrix, especially causes severe stress concentration in the matrix near interface[6]. The plastic flow of the matrix in SFR MMCs is also localized by the addition of fibre strongly[7-8]. These factors decrease the in-situ ductility of the matrix in SFR MMCs. Then, if the matrix's inherent ductility is good, the fibre may fracture when the matrix does not attain its strain hardening limit because the matrix in composites still has some plastic flow capability, so the matrix stress related to matrix strength should be low. But if the matrix's inherent ductility is bad, some local areas of the matrix in composites maybe has reached its strain hardening limit even has begun to fracture before the fibre fails. So when fibre's strain closes to fracture strain, the matrix stress should be high enough (even higher than matrix strength, i e matrix fractures firstly). Because the tensile ductility of Al-12Si is better than that of Al-12Si-Cu whose tensile ductility is better than that of Al-12Si-Mg, there should be σ'_m (Al-12Si) < σ'_m (Al-12Si-Cu) < σ'_m (Al-12Si-Mg) and $\dfrac{\sigma'_m}{\sigma_{um}(\text{Al-12Si})} < \dfrac{\sigma'_m\ (\text{Al-12Si-Cu})}{\sigma_{um}(\text{Al-12Si-Cu})} <$

$\frac{\sigma'_m (Al\text{-}12Si\text{-}Mg)}{\sigma_{um}(Al\text{-}12Si\text{-}Mg)}$.

In our experimental results:

σ'_m (Al-12Si) = 191.0 MPa;

σ'_m (Al-12Si-Cu) = 225.5 MPa;

σ'_m (Al-12Si-Mg) = 305.4 MPa;

$\frac{\sigma'_m (Al\text{-}12Si)}{\sigma_{um}(Al\text{-}12Si)} = 0.81$;

$\frac{\sigma'_m (Al\text{-}12Si\text{-}Cu)}{\sigma_{um}(Al\text{-}12Si\text{-}Cu)} = 0.91$;

$\frac{\sigma'_m (Al\text{-}12Si\text{-}Mg)}{\sigma_{um}(A;\text{-}12Si\text{-}Mg)} = 1.06$.

Apparently, they coincide with the above analysis perfectly.

4 CONCLUSIONS

(1) The prediction eqns. and curves of the three composites under the experimental conditions used in this work are worked out by LRM:

①For Al-12Si matrix

$\sigma_c = 624\varphi_f + 191$, $\sigma'_m = 191$ MPa, $\varphi_{min} = 5.23\%$, $\varphi_c = 7.21\%$

②For Al-12Si-Cu matrix

$\sigma_c = 450\varphi_f + 225.5$, $\sigma'_m = 225.5$ MPa, $\varphi_{min} = 3.22\%$, $\varphi_c = 5.00\%$

③For Al-12Si-Mg matrix

$\sigma_c = 64.3\varphi_f + 305.4$, $\sigma'_m = 305.4$ MPa, no φ_{min} and φ_c.

(2) σ'_m and $\frac{\sigma'_m}{\sigma_m}$ of composite increase with matrix strength increasing (or matrix ductility decreasing) caused by the addition of Cu or Mg alloy element, which results in the decreasing of the reinforcing effect of composites.

SYMBOLS

σ_c —Composite tensile strength;

σ'_{um} —Unreinforced matrix tensile strength;

σ_f —Fibre tensile strength;

σ'_m —Matrix stress when composite fails;

τ_i —Interfacial yield stress in composite;

δ —Composite elongation;

C_0 —Orientation factor;

φ_f —Fibre volume fraction;

l_c —Fibre critical length;

$\overline{l}$ —Fibre mean length;

d —Fibre mean diameter;

φ_{min} —Minimum volume fraction;

φ_c —Critical volume fraction;

$\frac{\sigma'_m}{\sigma_{um}}$ —Matrix stress level related to unreinforced matrix tensile strength when composite fails.

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