ON THE MECHANICAL BEHAVIOURS OF SiC WHISKER REINFORCED Al COMPOSITES BY POWDER METALLURGICAL PROCESS

I. Jeong, K. Oh, H. Lee, D. Lee, Y.W. Baek

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Abstract

Studies were undertaken to evaluate the tensile behaviour of SiC-reinforced Al composite made by powder metallurgical process, where Al 2124 and X7091 were used as matrix alloys. Although the measured tensile strength did not reach to the predicted value, it was higher than that of the wrought Al alloys and increased with increasing volumic fraction of SiC whisker. By modifying Fukuda's probabilistic theory of short fiber composite strength, it turned out that the composite strength is dependent mainly upon critical zone width, maximum whisker alignment angle and critical fiber length. Composite failure was attributed to matrix fracture with fine dimples and partially whisker pull-out due to whisker/matrix debonding.

1. Introduction

Silicon carbide reinforced aluminium alloy (SiCw/Al) metal matrix composites (MMCs) have exhibited improved physical and mechanical properties as compared to the wrought properties of the matrix alloy, such as high specific modulus and strength, low thermal expansion and good thermal stability, etc. The SiCw/Al composites can also be worked using near-conventional metallurgical processes and hence is inexpensive to produce compared to other MMC systems. Although the improved mechanical properties of the SiCw/Al composites are relatively well documented, the physical basis for the improvement in strength is still open to question.

The strength and failure behaviour of short fiber composites are complicated by the non-uniformity in fiber length and orientation. For unidirectional continuous fiber composites, under the assumption of isostrain in the fibers and matrix, the "rule of mixture" is often used to predict the strength of fiber-reinforced composites:

$$ Q_{cm} = Q_{m} \cdot V_t + Q_{m} \cdot (1-V_t) $$

where $Q_{cm}$ is the ultimate strength of composite, $V_t$, fiber volume fraction, $Q_{m}$, the matrix stress at the failure of composite. In short fiber composites, however, there are variations not only in fiber length but in fiber orientation. Therefore, the rule of mixture should be modified to:

$$ Q_{cm} = Q_{cm} \cdot V_t \cdot F(l_c/l_0) \cdot C_o + Q_{m} \cdot (1-V_t) $$

where $F(l_c/l_0)$ is the fiber length factor, $l_c$, critical fiber length, $l_0$, average fiber length, and $C_o$ is the fiber orientation factor.
In order to deal with the distributions of fiber length and fiber orientation, Fukuda and Cho have introduced two kinds of probability density function, and predicted the composite strength using the concept of "critical zone" proposed by Bader, et al. Their result was as follows:

\[
C_{cu} = \rho_{cu} V F_{cu} \left[ \int_{0}^{\pi} g(\theta) \cos \theta \, d\theta \right] \int_{0}^{\pi} h(\theta) \, d\theta \\
\times \left[ \int_{-\infty}^{\infty} \left( 1 - \frac{\theta}{\pi} \right) g(\theta) \, d\theta \right] h(\theta) \, d\theta \\
\times \left[ \int_{0}^{\pi} h(\theta) \, d\theta \right] + C_{cu} \left( 1 - V_f \right) \quad \text{---(3)}
\]

where \(g(\theta)\) and \(h(\theta)\) are the probability density function of fiber length distribution and fiber orientation distribution, respectively, and \(\bar{\theta}\) is the critical zone width.

In the present study, we investigated the tensile behaviours of the SiCw/Al composites with two kinds of Al alloy matrix (2124, X7091) which were fabricated by P/M method. The experimental results were compared with the theoretical values of the modified Fukuda model. Factors affecting the tensile strength of composites were estimated.

2. Experimental Methods

The composite materials investigated were aluminium alloys 2124, X7091 reinforced with 10, 20 vol.% of SiC whisker by powder metallurgical process. The process consisted of wet blending SiC whisker with inert gas atomized aluminium alloy powders made by Korea Nonferrous Metal Powder Co., and hot pressing to full density above the solidus temperature of the matrix. The billet was then hot extruded, resulting in a high degree of alignment of the SiC whiskers parallel to the extrusion direction.

Heat treatment of 2124 matrix composite consisted of solutionizing at 535°C for 1 h, water quenching and then aging at 190°C for 24 h, to produce a modified T6 condition. X7091 matrix composite was heat-treated by solutionizing at 493°C for 1 h, water quenching and then natural aging for 24 h, similar to the case of unreinforced alloy X7091.

Tensile tests were conducted on round tensile specimens of 4 mm in diameter, 50 mm in length with 20 mm gage length. To identify the failure mode, the tensile fracture surfaces and the degree of whisker alignment were examined by Scanning Electron Microscopy.
3. Results and Discussion

3-1. Mechanical Properties

Fukuda's assumption in deriving equation (3) that length distribution function and orientation distribution function are independent each other makes it impossible to integrate that equation except some limiting cases. In this study, assuming that there exist interrelationships between two distribution functions, equation (3) was modified as follows:

\[ \sigma_{cu} = \sigma_{fu} V_f \frac{\pi}{4} \int_0^{\theta_m} g(\theta) \cos \theta d\theta \int_0^{\beta_m} \left( 1 - \frac{L}{L_0} \right) g(\theta) \cos \theta h(l) dl \]

\[ \times \left[ \int_0^{l_c} \frac{L}{L_0} h(l) \int_0^{\beta_m} g(\theta) \cos \theta d\theta dl + \int_0^{l_c} \left( 1 - \frac{L_c}{L} \right) h(l) \int_0^{\beta_m} g(\theta) \cos \theta d\theta dl \right] \]

\[ + \sigma_{m}^* \left( 1 - V_f \right) \] -----(4)

Equation (4) was integrated numerically for each two types of distribution functions, as shown in fig.1. \( \sigma_{cu} \) was assumed to be 4900 MPa, and \( \sigma_{m}^* \) 420 MPa.

Fig.2 shows the tensile strength variations with respect to critical zone parameter, \( \beta \) at different \( g(\theta) \) and \( \theta_m \). It shows that the strength in case 2 is higher than in case 1. It should be noted that composite tensile strength is decreased largely with increasing \( \theta_m \) and decreasing \( g(\theta) \). It may be due to the fact that \( \beta \) is largely dependent upon the interaction distance between each microcrack, which are initiated by stress concentrations in matrix around the tips of short fibers, and \( \theta_m \) is related with the degree of whisker alignment.

Effects of type of \( h(l) \) and \( \theta_m \) on composite strength are shown in fig. 3, where it appears that composites with uniform fiber length have higher strength than those with variable fiber length despite the same average fiber length. Considering the fact that the rule of mixture contains only average values, this result may imply that it should be modified through statistical approaches.

Fig.4 shows the effects of \( \theta_m \), \( l_c \) on the composite strength, when short fibers with variable length are aligned unidirectionally. Critical fiber length, \( l_c \), is expressed as follows:

\[ l_c/\theta_m = \frac{\theta_m}{2} \]

where \( \theta_m \) is fiber diameter, \( \theta_m \) is matrix shear strength and \( \theta_m \) fracture strength of fiber. It should be noted that \( l_c \) is dependent mainly upon matrix shear strength, \( \theta_m \). In order to improve composite strength, matrix with higher \( \theta_m \) is required because composite strength increases with decreasing \( l_c \) and increasing \( \theta_m \). Further study on the factors affecting matrix shear strength will be continued.

\( \beta \) value could be estimated by the elasto-plastic finite element analysis, in which the stress concentration due to the presence of short fiber within matrix has been studied. Fig. 5 shows the effective plastic strain contour around the fiber tip with the aspect ratio 10 and 15. It indicated that the ratio of the width of plastic region with 0.5% of effective plastic strain to the short fiber length was 0.1. As the definition of \( \beta \) was thought to be similar to this ratio, 0.1 of \( \beta \) value was used in this study.

Comparison of the experimental data with the theoretical values is shown in fig.6. Although the experimental data did not reach to the predicted tensile strength, it was higher than that of the wrought Al alloys. SiC whisker was unidirectionally aligned above 16:1 of extrusion ratio as seen in fig.7.
3-2. Fractography

Fig. 8 and 9 shows the Scanning Electron Micrographs of tensile fracture surfaces of the composites with Al 2124 and X7091 matrix, respectively. Although the macroscopic failure of tensile specimen might be seen brittle mode, it showed typical ductile fracture with fine matrix dimples. Some whisker pull-out sites were also observed on the fracture surfaces. Therefore, failure mode seems to be attributed to matrix fracture and whisker/matrix debonding in part, but not whisker breakage.

In case of 2124 matrix composites, number of whisker pull-out sites increased and dimple size became a little larger, with increasing vol. % of SiC whisker. However, there were little changes in X7091 composite. As can be seen in fig.10, whisker clustered and non-infiltrated regions were also found, which were thought to act as crack initiation sites.

4. Conclusions

The following conclusions were obtained:

1. Through theoretical approaches on the basis of modified Fukuda's probabilistic model, it turned out that the tensile strength of short fiber composite is dependent mainly upon critical zone parameter, $\rho$, max. fiber alignment angle, $\theta$, critical fiber length, $l_c$.

2. Although the measured tensile strength did not reach to the predicted value, it was higher than that of the wrought Al alloys and increased with increasing volume fraction of SiC whisker.

3. Composite failure was attributed to matrix fracture with fine dimples and partially whisker pull-out due to whisker/matrix debonding.

References

Fig. 1 Assumed Orientation and Length Distributions Function

Fig. 2 The Tensile Strength Variation with respect to Critical Zone Parameter, $\beta$ at Different $g(\theta)$ and $\theta$.

Fig. 3 The Effects of Type of Length Distribution Function, $h(l)$ and Average Fiber Length, $l$ on Composite Strength

Fig. 4 The Effects of Average Fiber Length and Critical Fiber Length on the Composite Strength
Fig. 5 The Effective Plastic Strain Contour around the Fiber Tip with Aspect Ratio (a) 10, (b) 15

Fig. 6 Composition of the Experimental Data with The Theoretical Values
Fig. 7 Unidirectionally Aligned SiC Whiskers above 15:1 of Extrusion Ratio.

Fig. 8 Scanning Electron Micrographs of Tensile Fracture Surfaces of the Composite with Al 2124 Matrix.
(a) 10 vol. % of SiC (b) 20 vol. % of SiC

Fig. 9 Scanning Electron Micrographs of Tensile Fracture Surfaces of the Composite with Al X7091 Matrix.
(a) 10 vol. % of SiC (b) 20 vol. % of SiC

Fig. 10 Scanning Electron Micrographs of Whisker Clustered and Non-Infiltrated Region.