Note

Effect of Fiber Volume Fraction and Test Method on the Scatter of Strength in Carbon Fiber-reinforced Aluminum Composite

1. Introduction

Advanced fiber-reinforced metal matrix composites are considered materials with potential for structural use. These advanced composites, reinforced with strong but brittle fibers, often fail catastrophically like engineering ceramics. When the metal matrix composite fails in brittle fashion, the scatter of strength in the composite often increases and this causes severe problem; strength of the composite should be assured before its use as a load-bearing component.

The scatter of strength in fiber-reinforced plastics has been discussed using the Weibull statistical method and applicability of the Weibull statistical model was determined based on experimental results.¹⁻⁴⁾ Very little experimental work has been reported on the scatter of strength especially in small diameter, approximately on the order of $10\mu\text{m}$, fiber-reinforced metals.⁵⁻⁷⁾ Previous reports^{5,6)} described the scatter of strength in SiC fiber-reinforced aluminum using the Weibull statistical method, and dependence of the strength of the composite on the test method used was discussed based on the effective volume in the specimen. These studies, however, were only a simple approximation and the effect of failure behavior of the composite on the scatter of strength was not included in the analysis. The present study, attention has been focused on the effects of volume fraction of the composite on the scatter of strength in carbon fiber-reinforced aluminum.

2. Experimental Procedure

The matrix metal, commercial purity 99.9 wt% aluminum, was unidirectionally reinforced with high strength type continuous carbon fiber (T-300, Toray, Japan). The elastic modulus and strength of the as-received fiber were 250 and 3 GPa, respectively. The volume fraction of the fiber was 0.25 and 0.65. The composite was fabricated by the conventional squeeze casting procedure, the details of the process are reported elsewhere.⁸⁾ On the microstructure of this composite each carbon fiber was surrounded by aluminum matrix and that was slight memory of the location of the individual fiber tows (see Fig. 3) and some of the aluminum rich area spread inter-tow regions.

Mechanical test specimens were cut from as-cast ingots using an arc-discharging machine and then ground to the final dimensions using a standard metal-lurgical technique. Dimensions of the test specimens were: length 100 mm, width 5 mm, thickness 2 mm.

Tensile and bend-tests were carried out at room temperature (297 K) using an Instron-type universal testing machine. Crosshead speed was 8.33×10^{-6} m/s in all tests. The gage length of the tensile test specimen was 30 mm and a commercially pure aluminum tabbed specimen was used. For all the bend tests, the major span length was 40 mm and the minor span length of the four-point bend-test was 20 mm. More than 15 composite specimen were tested under the same conditions of testing method and volume fraction, respectively.

After the tests, the fracture surfaces of the selected specimen were observed by scanning electron microscope (SEM) to determine the fracture morphology of the composite.

To evaluate the strength of the carbon fiber after its incorporation into the aluminum matrix, the aluminum matrix was dissolved in a 30% hydrochloric acid solution of 300 K. The extracted fibers were tensile-tested and the average tensile strength and the Weibull modulus of the fiber was obtained by a modified form of the Weibull treatment.⁹⁾ In this case, gage length was 15 mm and approximately 50 pieces of the extracted fibers were tested. The crosshead speed and other testing conditions were the same as for the composite tensile testing.

3. Results and Discussion

Figure 1 shows plots of the average strength of the composite vs. volume fraction of the fiber. For the three-point and four-point bend tests, the stress at failure, σ_{3b} and σ_{4b} , were calculated as:

Fig. 1. Variation of the Weibull modulus of the composite with fiber volume fraction for tensile, three-point bend, and four-point bend-tested composites.

Fig. 2. Plots of fracture stress with volume fraction of fiber for tensile, three-point bend, and four-point bend-tested composites.

$$\sigma_{3b} = \frac{3F_f}{2bd^2} \dots\dots\dots(1)$$

$$\sigma_{4b} = \frac{3F_f(L-L^*)}{2bd^2} \dots\dots\dots(2)$$

where F_f is the fracture load, L ($=40$ mm) and L^* ($=20$ mm) are the major and the minor span length respectively, b is the specimen width ($=5$ mm), and d is the specimen thickness ($=2$ mm). As shown in Fig. 1, the reinforcing efficiency of the fiber decreased with increasing volume fraction of the fiber.

Figure 2 shows a variation in the Weibull modulus of the composite, m_c , with the fiber volume fraction. In this case, the Weibull modulus was obtained using a two-parameter statistical distribution. According to Weibull's statistical method¹⁰⁾ the probability of failure, P_F , of the composite with stress, σ_c is given as:

$$P_F = 1 - \exp \left[-V \left(\frac{\sigma_c - \sigma_u}{\sigma_0} \right)^{m_c} \right] \dots\dots\dots(3)$$

where m_c is the Weibull modulus of the composite, V is the volume of composite (effective volume) and σ_0 is a normalizing parameter of no physical significance. The Weibull modulus of the composite, m_c , can be determined by rearranging into the form of:

$$\ln \ln \left[\frac{1}{(1-P_F)} \right] = m_c \ln(\sigma_c - \sigma_u) - m_c \ln \sigma_0 + \text{Const.} \dots\dots\dots(4)$$

In Eq. (4), the probability of failure P_F at or below stress σ_u can be defined from mean rank method as:

$$P_F = \frac{n}{N+1} \dots\dots\dots(5)$$

where N is the number of samples and n is the n th rank sample. The experimental data defining P_F as a function of σ_u can then be least squares fit to the linear relationship of Eq. (4), thus defining m_c .

The Weibull modulus of the composite, m_c , decreased with increasing fiber volume fraction, this relation was

Fig. 3. Typical fracture appearance of the tested specimens: ((a) tensile-tested specimen, (b) three-point bend-tested specimen, (c) four-point bend-tested specimen.

independent of the test method. The Weibull modulus of the carbon fiber extracted from as cast composite was $=5.4$ with the average strength of 2.2 GPa. Consequently, the Weibull modulus of the composite was always larger than that of the extracted bare carbon fiber.

When the dependence of the Weibull modulus of the composite on the test methods was compared with the same volume fractions, the Weibull moduli increased in the order of three-point bend-test, four-point bend-test, and tensile test. The difference of the Weibull modulus on the test methods was reported earlier^{5,6)} and analyzed using the factor of effective volume of the composite material, which depended on the test method and dimensions of the specimen. In this study, however, the Weibull modulus of the composite differed with the test method used even in the same volume fractions. This dependence could not only explained in terms of the effective volume of the composite during the testing.

Figure 3 shows a typical SEM photograph of the

Fig. 4. Fracture appearance of the three-point bend-tested specimen near the neutral axis.

fracture surface for tensile and bend-tested specimens. The overall fracture surface of the tensile-tested specimen was smooth, while that of the three-point bend-tested specimen differed within the specimen. On the tension side of the three-point bend-tested specimen, the failure surface was relatively smooth and was the same as the tensile-tested specimen. Fiber-matrix interfacial slips, shear failure of the fibers, and longitudinal fiber failure nearly halfway through the thickness of the specimen (Fig. 4). These failure behaviors suggested that a large shear force was acting near the neutral axis while the specimen was bend-tested.⁷⁾ In addition, compressive failure of the composite was recognized at the compressive side of the three point bend-tested

specimen. The difference of the Weibull modulus in this study is considered due to the fracture process of the composite by the various test methods. The fracture appearance of the four-point bend-tested specimen was similar to that of the three-point bend-tested specimen, though no remarkable shear failure was recognized in the surface.

4. Concluding Remarks

The experimental results show that the Weibull modulus of fracture stress of the composite decreases with increase in the fiber volume fraction. However, within the same volume fraction, the Weibull modulus differs with the test method employed due to differences in the fracture process. When the failure process differs, application of the Weibull's theory seems less appropriate, because Weibull's statistical treatment is based on the weakest link theory which assumes that the weakest point of the composite remains unchanged during the failure process.

Therefore, it seems difficult to apply and analyze the difference in strengths measured by the tensile and bend-tests using the Weibull's statistical method. When we use this statistical treatment to evaluate the strength of the composites, failure behavior should be considered. It must also be kept in mind that the Weibull modulus of the composite is not a material constant because of the modulus is affected by the failure process.

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