Transactions on Engineering Sciences vol 13, © 1996 WIT Press, www.witpress.com, ISSN 1743-3533

Application of incremental damage theory to glass particle reinforced Nylon 66 composites

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Abstract

In this paper, tensile tests are carried out on seven kinds of glass particle reinforced nylon 66 composites in which a particle volume fraction is varied in 0%, 10%, 20% and 30%, and glass particles treated or untreated with silan-coupling are used. The stress-strain response of the composites depends on both the particle volume fraction and the treatment of interface between the particles and matrix. Young's modulus and Poisson's ratio are characterized by only the particle volume fraction, while tensile strength is described as a function of the particle volume fraction and interface treatment. With increasing particle volume fraction, the tensile strength increases first and then becomes constant in the interface-treated composites, and decreases in the interface-untreated conventional composites. Numerical analysis is also carried out on stress-strain response and damage behavior of the seven kinds of composites. The stress-strain relations of the interface treated composites are explained only by influence of particle volume fraction while those of the conventional composites are characterized by considering the particle volume fraction and interfacial debonding between the particles and matrix.

1 Introduction

In particle-reinforced ductile-matrix composites, cracking or debonding damage of particles develops from early stage of deformation and the damage process strongly affects the deformation and strength of the composites. Authors investigated the mechanical properties and fracture mechanism in a spheroidized cementite steel in which hard particles are dispersed in a soft ferrite matrix (e.g. Tohgo, Suzuki & Ishii[1]). According to their results, the hard particles have not only a reinforcing effect but a weakening effect due to the damage, and a interfacial strength between particles and matrix is another important factor as well as the mechanical properties of the particles and matrix and a particle content, which control the performance of the composites. Furthermore, one of the authors developed a incremental damage theory of particle-reinforced composites taking into account the plasticity and the debonding damage (e.g. Tohgo & Chou[2], Tohgo & Weng[3]). In order to extend the application of particle-reinforced composites and to develop a new composite system, the micro-mechanism of fracture in the composites should be clarified.

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In this investigation, tensile tests and simulation analysis based on the damage theory were carried out on seven kinds of glass particle reinforced nylon 66 composites, in which the particle volume fraction and surface treatment of the particles were varied. Influence of the particle content and interfacial strength on the deformation, strength and damage process in the particle-reinforced composites were discussed.

2 Experimental procedure

The materials are a nylon 66 and six kinds of glass particle reinforced nylon 66 composites in which a particle volume fraction is varied in 10%, 20% and 30%, and glass particles treated or untreated with silan-coupling are used. An average diameter of the spherical glass particles is 17μm, and the surface treatment of glass particles is given with silan-coupling to improve the interfacial strength between the particles and matrix. The composite containing untreated particles is referred as *interface-untreated composite* or *conventional composite,* while the composite containing treated particles is referred as *interface-treated composite*. Furthermore, these materials are represented by GN-0 for the nylon 66, by GN-10, GN-20 and GN-30 for the conventional composites, and by GNIT-10, GNIT-20 and GNIT-30 for the interface-treated composites, using a number of the particle volume fraction. Tensile specimens are the ASTM D638-Type I, which were fabricated by injection molding. Tensile tests were conducted on three specimens for each material with cross-head speed of 1mm/min at room temperature. During test, the load was recorded against the strain measured by a strain gauge with 5mm gauge length for each specimen.

3 Experimental results

3.1 Stress-strain relation and mechanical properties

Figure 1 shows stress-strain relations obtained for each material. Each curve represents the stress-strain relation for each material by intermediate property in three specimens. Young's modulus, Poisson's ratio, tensile strength and ductility obtained from stress-strain relations are shown as a function of a glass particle volume fraction in Fig. 2. The ductility is expressed by a nominal strain at final fracture for 50mm gauge length. The stress-strain response strongly depends on a

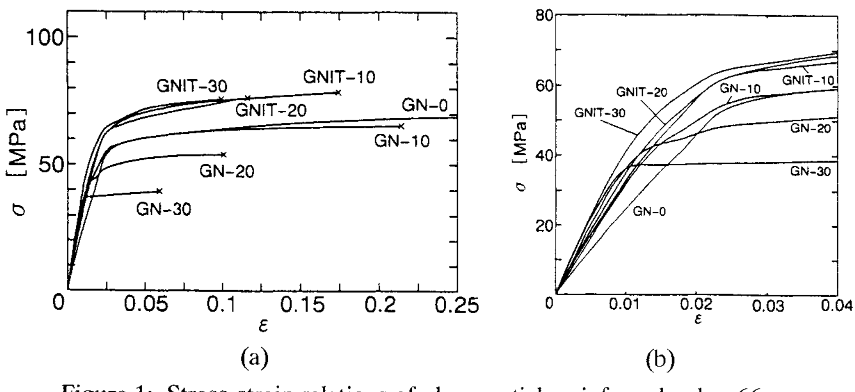

Figure 1: Stress-strain relations of glass particle reinforced nylon 66 composites under uniaxial tension.

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particle volume fraction and the surface treatment of glass particles, as shown in Fig. 1. Especially it is noted that the interface-treated composites are strengthened with particles while the interface-untreated conventional composites are weakened with particles. The Young's modulus increases and the Poison's ratio decreases with an increase in the particle volume fraction, irrelevant to the interface treatment. With increasing the particle volume fraction, the tensile strength increases at first and then becomes constant in the interface-treated composites, and decreases in the conventional composites. The influence of the interface treatment is not observed on the ductility which is characterized by reduction with the particle volume fraction.

3.2 Fractography and damage mechanism

Micrographs of fracture surface are shown for the composites with 10% and 30% particle volume fraction in Fig. 3. Morphology of fracture surface depends on the interface treatment. In the conventional composites, the fracture surface is covered with the smooth glass surface and ductile dimple pattern which are the evidence of the interfacial debonding between the grass particles and matrix. On the other hand, the interface-treated composites exhibits the appearance of the surface fractured in brittle manner where the matrix resin adheres to the glass particles.

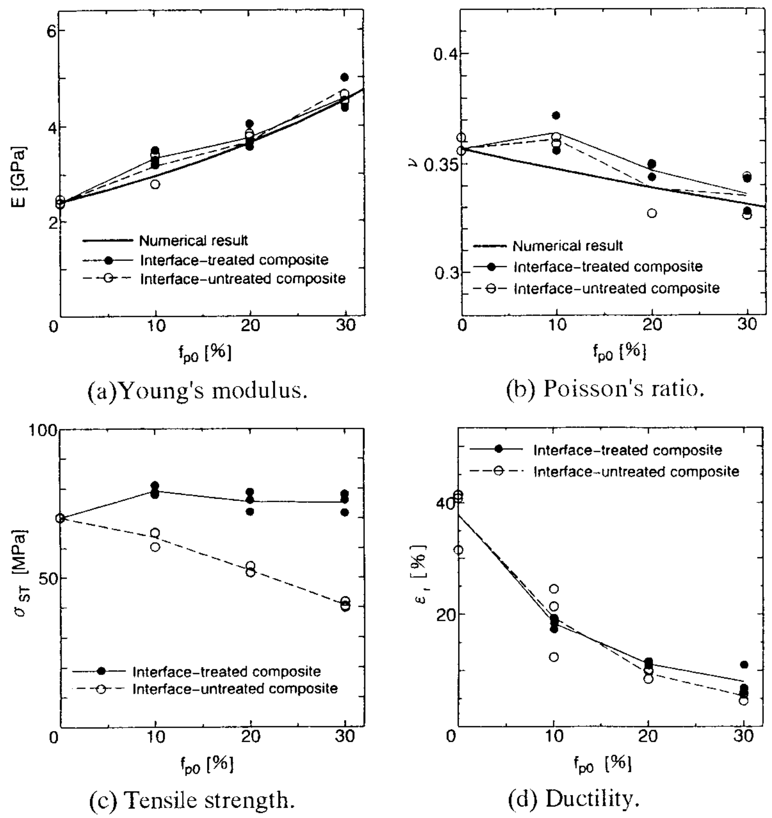
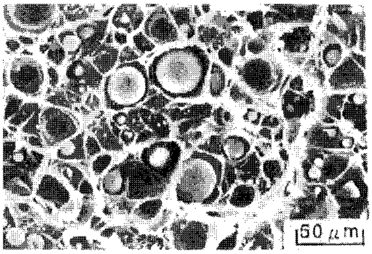
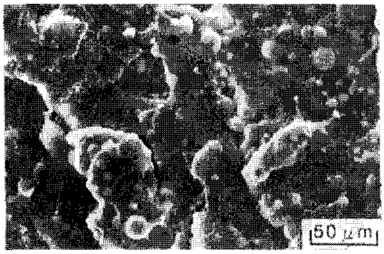


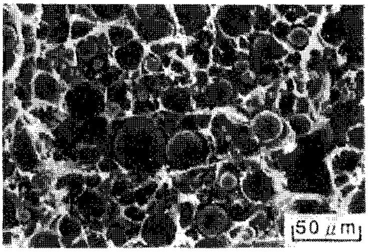
Figure 2: Tensile Properties as a function of a particle volume fraction.



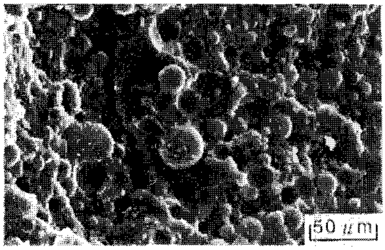
(a) GN-10.



(b) GNIT-10.

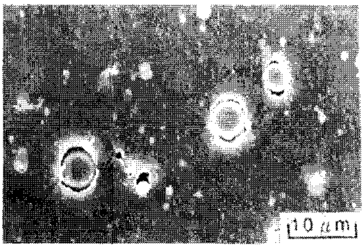


(c) GN-30.

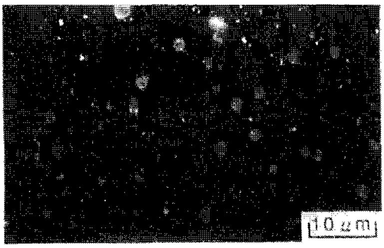


(d) GNIT-30.

Figure 3: Micrographs of fracture surfaces.

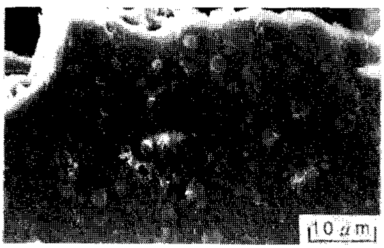


(a) GN-10.



(b) GNIT-10.

(c) GN-30.



(d) GNIT-30.

Figure 4: Micrographs of specimen surfaces.

Figure 4 shows the micrographs of the side surface near the fractured region for the composites with 10% and 30% particle volume fraction. In these figures, the damage developed up to the final failure can be observed. It is noted that the damage morphology depends on the interface treatment. In the conventional

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composites, the void nucleation occurs by debonding of the particle-matrix interface and the particles inside voids seem to completely lose a load carrying capacity. The interface-treated composites exhibit less particles encountering the damage which is the cracking damage in the matrix near the particles or the debonding damage with adhesion of matrix resin to glass particle. Such damaged particles still maintain the load carrying capacity.

The difference in the stress-strain relations and mechanical properties is attributed to the difference in the damage process. In the conventional composite the interfacial strength is low and the debonding damage is easy to occur, while in the interface-treated composite the interfacial strength is improved by the surface treatment of the glass particles with silan-coupling. Young's modulus and Poisson's ratio are the same on both materials because these elastic properties were determined by initial deformation before nucleation of debonding damage. With increasing stress level, the difference in the damage process comes out, and the tensile strength of the interface-treated composite is much higher than that of the conventional composite. The influence of the interface treatment is more outstanding in the composite with higher particle volume fraction.

4 Numerical results and discussion

As mentioned in the previous section, the deformation and strength of particle-reinforced composites depend on the interfacial strength as well as the mechanical properties and the particle volume fraction. In order to describe the influence of the interfacial debonding and the plasticity of the matrix, Tohgo & Chou[2] and Tohgo & Weng[3] developed an incremental damage theory based on Eshelby's equivalent inclusion method (e.g. Eshelby[4]) and Mori-Tanaka's mean field concept (e.g. Mori & Tanaka[5]), under the following assumptions.

(1)The debonding of particles is controlled by the stress and the statistical behavior of the particle-matrix interfacial strength.

(2)During debonding, the stress of the debonded particles is released and as the debonded particle loses the load carrying capacity, the site of the particle is regarded as a void.

(3)The volume fraction of the debonded particles turns into the void volume fraction.

Here, a simulation analysis for the tensile test of the glass particle reinforced nylon 66 composites was carried out based on this incremental damage theory, and the influence of debonding damage on the performance of the composites was discussed.

4.1 Mechanical properties of the particles and matrix

Young's modulus E_0, Poisson's ratio ν_0, yield stress σ_0 and equivalent stress-equivalent plastic strain relation of the matrix were determined by the experimental stress-strain relation for Nylon 66 GN-0 as follows;

$$E_0 = 2.41\ (\mathrm{GPa})\,, \qquad \nu_0 = 0.36\,, \tag{1}$$

$$\sigma_0 = 50.0\ (\mathrm{MPa})\,, \tag{2}$$

and

$$\sigma_e^0 = 2.82\left(1 + \frac{\varepsilon_e^{0p}}{2}\right)^{0.07}\,. \tag{3}$$

The elastic properties of the particle were determined so that Young's modulus and Poisson's ratio of composites fit to the experimental results (Fig. 2) on the elastic analysis using the above Young's modulus and Poisson's ratio of matrix. The Young's modulus and Poisson's ratio of the particle which gave good agreement are as follows:

$$E_1 = 100\ (\mathrm{GPa}), \qquad \nu_1 = 0.20\ . \tag{4}$$

Solid lines in Fig. 2 (a) and (b) show the numerical results. It is assumed that the interfacial strength between the particle and matrix is described by the following Weibull distribution in terms of the maximum stress of the particles:

$$P_v(\sigma^p_{max}) = 1 - \exp\left[-\left(\frac{\sigma^p_{max}}{S_0}\right)^m\right], \tag{5}$$

where m and S_0 are the shape parameter and scale parameter, respectively. The average interfacial strength is given by

$$\bar{\sigma}^p_{max} = S_0\,\Gamma\left(1 + \frac{1}{m}\right), \tag{6}$$

where $\Gamma(\cdot)$ is Gamma function.

4.2 The interface-treated composites

Figure 5 shows the experimental and numerical stress-strain relations for the nylon 66 GN-0, and the interface-treated composites GNIT-10, GNIT-20 and GNIT-30. The numerical results were obtained under the assumption of no debonding damage. Although the numerical stress-strain relation of f_{p0}=10% shifts to the lower side of stress from the experimental result, on the composites with f_{p0}=20% and 30% both numerical and experimental results give good agreement. These results indicate that in the interface-treated composites the debonding damage during deformation is very reduced owing to the improvement of the interfacial strength between the particles and matrix, and are consistent with the observation of the fracture surfaces and side surfaces in section 3.2.

4.3 The conventional composites

In the analysis for the interface-untreated conventional composites GN-10, GN-20 and GN-30, two approaches were tried by taking account of the debonding damage. In the first approach, the numerical stress-strain relations were obtained under the condition of the debonding parameters m=3.2 and $\bar{\sigma}^p_{max}$=91.0MPa which were determined so that the experimental and numerical stress-strain relations for GN-20 to give a good agreement. Figure 6 shows the experimental and numerical stress-strain relations obtained by the first approach. In this figure, the damage evolution is also shown by a volume fraction of the deboned particles f_v. It is found from Fig. 6 that the numerical results shift to the lower side of stress for GN-10, and to the higher side for GN-30, respectively. This suggests that the stress-strain relation of the conventional composite cannot be explained by the debonding damage under the constant debonding parameters.

On the following approach, the numerical analysis was carried out so that the numerical stress-strain relation to fit the experimental result on each composite as shown in Fig. 7, and then the debonding parameters m and $\bar{\sigma}^p_{max}$ were determined for each composite. Figure 8 shows the Weibull distributions for the interfacial

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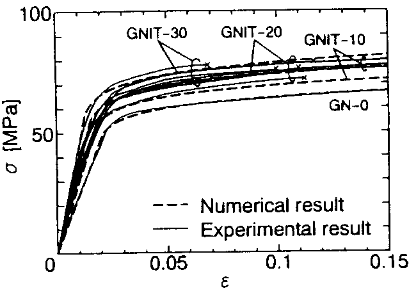

Figure 5: Stress-strain relations of the interface-treated composites.

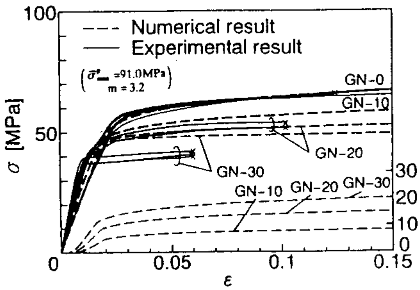

Figure 6: Stress-strain relations of the conventional composites. Numerical results are obtained under the debonding properties for GN-20.

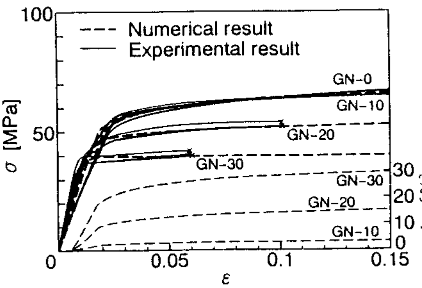

Figure 7: Stress-strain relations of the conventional composites. Numerical results are obtained to fit each materials.

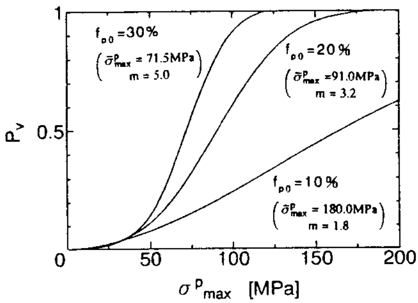

Figure 8: Weibull distribution for interfacial strength of particles and matrix.

strength of each composite obtained in the second approach. As shown in Fig. 8, with increasing the particle volume fraction, the average debonding stress $\bar{\sigma}^{p}_{max}$ decreases and the shape parameter m increases. As a results, the Weibull distribution at low stress level which corresponds to the early stage of damage process is almost the same in all composites, but in the succeeding stage the composite with higher particle volume fraction shows severer damage accumulation.

Consequently, the stress-strain relations of the conventional composite can be explained by the influence of debonding damage and the decrease in interfacial strength with an increase in particle content. However, it is hard to imagine that the interfacial strength between the particle and matrix in the same composite system depends on the particle content. This is presumed as follows. The distribution of particles such as mean distance and local density depends on the particle volume fraction. On the composite with high particle content, for example, the particles are close each other and the regions of high particle density are easily created. Furthermore, in the regions of high particle density one damaged particle leads to another damage on the neighbor particles because the stress release of the damaged particle enhances the stress level of the surrounding matrix and particles. Therefore, in contrast with random occurrence of the debonding damage on the composite with dilute particle content, the debonding damage on the composite with

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high particle content is more localized. The incremental damage theory used in the present analysis was developed under the assumption of homogeneous distribution of the intact and damaged particles in the matrix. It is supposed that the influence of such localized damage appears as if the interfacial strength depends on the particle volume fraction.

5 Conclusions

The conclusions obtained by the present investigation are summarized as follows:

(1) The stress-strain relations of glass particle reinforced nylon 66 are affected by the particle volume fraction and the interface treatment between the particles and matrix.

(2) The interface-untreated conventional composites exhibit the debonding damage of the interface during the deformation and their fracture surfaces are covered with typical dimple pattern. On the other hand, the interface-treated composites shows a little crack-like damage near the particles.

(3) According to the simulation analysis based on the incremental damage theory, the stress-strain responses of the interface-treated composites are explained only by influence of particle volume fraction while those of the conventional composites are characterized by considering the particle volume fraction and interfacial debonding.

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