Evaluation of Initiation of the Interfacial Debonding in Single Fiber Composite
(Energy Balance Method Considering an Energy Dissipation of the Plastic Deformation)

Souta KIMURA**, Jun KOYANAGI** and Hiroyuki KAWADA***

Fiber-matrix interfacial adhesion in composites is traditionally evaluated by means of a stress-based parameter. Recently, an interfacial energy parameter is suggested to be a valid alternative. However, the energy-based approaches overestimated the energy release rate to initiate the interfacial debonding (interfacial energy), since the plastic deformation in the vicinity of the debonding was neglected for simplicity. An effect of the plastic deformation on the interfacial energy of a fiber-reinforced polymer matrix composite is studied to evaluate the initiation of the interfacial debonding. The fragmentation tests with a model of glass fiber-reinforced vinyl-ester matrix composite were performed, and the interfacial energy with the energy balance method taking into account an energy dissipation of the plastic deformation was calculated. The following results are confirmed; the plastic deformation has a significant influence on the interfacial energy, and the energy balance scheme taking into account the plastic energy dissipation leads to the constant interfacial energy without reference to the amount of the released potential energy. The differences between our model and the previous one are discussed.

Key Words: Interfacial Energy, Energy Balance Method, Plastic Deformation and Fragmentation Test

1. Introduction

One of the most principal problems in the fiber-reinforced plastics (FRP) lies on the control of the adhesion between the matrix and fiber. In many researches, the fiber-matrix interfacial adhesion is traditionally evaluated by means of a stress-based parameter using a fragmentation test. The stress-based approaches are divided into two categories; one is an application of an interfacial maximum shear stress (Cox model)(1), the other an interfacial mean shear stress (Kelly-Tyson model)(2). However, the stress-based methods are inadequate to assess the interfacial adhesion quantitatively, since both the interfacial maximum and mean shear stresses don’t give any criterion of interface fracture. Recently, the energy release rate to initiate the interfacial debonding (interfacial energy) is suggested to be valid for the evaluation of the interfacial property(3) – (6). Wagner et al.(3) have proposed an energy balance scheme for an analysis of the initial interfacial debonding which occurs simultaneously with a fiber break during a fragmentation test, and calculated the interfacial energy. Nevertheless, the energy-based approach is not fully developed, since the plastic deformation in the vicinity of the debonding is neglected for simplicity. Therefore, the interfacial energy obtained from the previous models is overestimated, and varies along with an amount of a potential energy released with a fiber break.

Our main goal is to propose an energy balance method taking into account an energy dissipation of the plastic deformation for the analysis of the interfacial energy. We performed a fragmentation test with a model of ECR glass fiber-vinyl-ester matrix composite. The plastic region around the debonding accompanying a fiber break was defined analytically, and the energy dissipation was calculated. To confirm the validity of the present model,
we performed the fragmentation test using the specimens with different fiber strength holding the same surface condition. The interfacial energy obtained from the present energy balance method resulted in a constant value without reference to the amount of the released potential energy.

The remainder of the present paper is structured as follows. In section 3, an energy balance method considering the plastic deformation is described for the analysis of the interfacial energy. In section 4, the stress distribution around the debonding and the plastic zone is described. In section 5, the procedure of the fragmentation test is described. In section 6, the discussion is conducted for the quantitative evaluation of the degree of the interfacial adhesion by means of the interfacial energy derived from the present energy balance method.

2. Nomenclature

\[ \sigma : \text{fiber radius} \]
\[ b : \text{effective matrix radius} \]
\[ E : \text{Young's modulus} \]
\[ G : \text{shear modulus} \]
\[ \nu : \text{Poisson's ratio} \]
\[ c : \text{coefficient of thermal expansion} \]
\[ L_d : \text{interfacial debonding length} \]
\[ \gamma : \frac{a^2}{b^2-a^2} \]
\[ \sigma_t : \text{modulus' ratio} \left( = \frac{E_m}{E_f} \right) \]
\[ \Gamma : \text{energy release rate to initiate an interfacial debonding (interfacial energy)} \]
\[ \Gamma_f : \text{fiber toughness} \]
\[ \Gamma_m : \text{matrix toughness} \]
\[ \sigma_{\text{c}} : \text{applied stress} \]
\[ \tau_{\text{sy}} : \text{matrix shear yield stress} \]
\[ \epsilon_c : \text{applied strain} \]
\[ \sigma_{\text{ia}} : \text{interfacial shear stress} \]
\[ r_p : \text{remote axial fiber stress} \]
\[ r_p : \text{radial coordinate of the end of the matrix yielding zone} \]
\[ z_p : \text{axial coordinate of the end of the matrix yielding zone} \]
\[ \Delta T : \text{temperature difference during the cure} \]

In the texts, subscripts \( f \) and \( m \) denote the fiber and matrix, respectively, and each superscript denotes the coordinate axis.

3. Energy Balance Method

3.1 The previous models

Wagner et al.\(^{(3)}\) have proposed an energy balance method that the released potential energy is transformed into an energy contribution necessary for the formation of a fiber-break surface, and into a contribution necessary for the formation of an interfacial debonding during the fragmentation test. Their energy balance equation is the following form:

\[
\left[ U_{j}^{\text{prior}} - U_{j}^{\text{post}} \right] + \left[ U_{m}^{\text{prior}} - U_{m}^{\text{post}} \right] = 4\pi a \cdot L_d \cdot \Gamma_i + \pi a^2 \Gamma_f
\]

where \( U_{j}^{\text{prior}} \) and \( U_{j}^{\text{post}} \) are the strain energies stored in intact region before and after the fiber fracture, respectively. An expression of the interfacial energy derived from Eq. (1) is written as

\[
\Gamma_i = \frac{\sigma_{\text{c}}^2 \alpha^2}{4 E_f L_d} \left( \frac{L_d}{2} + \frac{1}{\beta} - \frac{1}{16 G_f} \right) \frac{1}{4 L_d} \Gamma_f
\]

where

\[
\beta = \frac{1}{a} \sqrt{\frac{2G_m}{E_f \ln(b/a)}}
\]

Yallee and Young\(^{(5)}\) have developed this approach to estimate the interfacial debonding-initiation energy for fiber-matrix interfaces debonded from fiber ends before fiber break. Wagner et al.\(^{(4)}\) have included an effect of the interfacial friction in the debonding zone in Eq. (1), and thus the energy balance is the following form:

\[
\left[ U_{j}^{\text{prior}} - U_{j}^{\text{post}} \right] + \left[ U_{m}^{\text{prior}} - U_{m}^{\text{post}} \right] = \left[ U_{\text{frict}} + U_{\text{frict}}^m \right]
\]

where \( U_{\text{frict}} \) is the strain energy stored in debonding region, and an expression of the interfacial energy is

\[
\Gamma_i = \frac{\sigma_{\text{c}}^2 \alpha^2}{4 E_f L_d} \left[ 1 - \frac{(1-t)^2}{3} \cdot \frac{t(4-t)}{\beta \lambda L_d} \right]
\]

\[
\gamma = \frac{2 S E_f a^2}{L_d} \left[ \frac{\beta \lambda^2}{4} + \frac{(1-t)^2}{L_d} \right] - \frac{a \Gamma_i}{4 L_d}
\]

where \( t = 1 - (\psi L_d/a), S = \frac{1}{4 G_f} + \frac{1}{G_m} \ln(b/a) \) and

\[
\beta_i = \frac{2}{a^2 E_f E_m} \left[ \frac{E_f V_f + E_m (1 - V_f)}{a^2 V_f + \frac{1}{4 G_f} \left( \frac{1}{1 - V_f} \ln(1/V_f) - \frac{3}{2} \right)} \right]
\]

where \( \psi \) is interfacial friction factor and \( V_f = a^2/b^2 \).

3.2 The present model

The energy balance methods described in the previous section are neglecting the plastic deformation in the vicinity of an interfacial debonding. A typical result for a single fiber break of ECR glass/vinylester composite is shown in Fig. 1.

Obviously, a group of slip bands around the debonding is observed in Fig. 1, so it is unable to neglect the large-scaled plastic deformation in the case of a polymer-matrix composite that the more rigid fiber is embedded in the more ductile matrix. In addition to the plastic deformation, a matrix crack at fiber-break point is also observed in Fig. 1. Consequently, the energy balance equation including both the plastic deformation and matrix crack effects is written as

\[
\left[ U_{j}^{\text{prior}} - U_{j}^{\text{post}} \right] + \left[ U_{m}^{\text{prior}} - U_{m}^{\text{post}} \right] = 4\pi a \cdot L_d \cdot \Gamma_i + \pi a^2 \Gamma_f
\]
Matrix crack

Fig. 1 Photograph in the vicinity of a fiber-break point of ECR glass/vinylester composite

\[ U_{prior}^{prior} - U_{prior}^{out} + U_{m}^{elastic} - U_{m}^{plastic} \]
\[ - [U_{m}^{frict} + \tau_{frict}] \]
\[ = 2\pi a L_{d} \Gamma_{i} + \frac{\pi}{2} (r_{c}^{2} - a^{2}) \Gamma_{m} + \frac{\pi a^{2}}{2} \Gamma_{f} \]  
\( (7) \)

where \( U_{m}^{elastic} \) and \( U_{m}^{plastic} \) are the strain energy stored in the matrix of intact zone after fiber break and the energy dissipation of the plastic deformation, respectively, and \( r_{c} \) is the radius of the matrix crack.

4. Stress Distribution

A fiber break is accompanied by the simultaneous formation of an interfacial debonding region and a plastic region (Fig. 2). Obviously, the matrix in the vicinity of the debonding tip is under a complex stress state, including axial, radial, circumferential and shear stresses. For simplicity, we assume that due to the much higher longitudinal fiber modulus, shear stress prevails in the matrix. Moreover, we consider matrix perfect plasticity and let the interfacial shear stress in the plastic zone be equal to the matrix shear yielding stress \( \tau_{ym} \).

4.1 Debonding region

The shear-lag equation is given by
\[ \frac{d\gamma_{f}}{dz} = \frac{2}{a} \tau_{i} \]  
\( (8) \)

and a mechanical equilibrium condition between \( \sigma_{c} \) and the internal stress components is given by
\[ b^{2} \sigma_{c} = a^{2} \sigma_{f} + 2 \int_{b}^{b} r \sigma_{m} dr \]  
\( (9) \)

A radial stress, \( q(a,z) \), acts at the interface that arises from the differential Poisson contraction between the fiber and matrix. \( q(a,z) \) is obtained from the continuity of circumferential strain at the interface\(^{8}\),
\[ q(a,z) = \frac{\alpha_{f}}{\alpha(1 - \nu_{f}) + 1 + \nu_{m} + 2\nu} + q_{th} \]  
\( (10) \)

where \( q_{th} \) is a thermal residual stress due to specimen preparation and written as

\[ q_{th} = \frac{2G_{f}G_{m} \Delta T [(1 + \nu_{m})c_{m} - (1 + \nu_{f})c_{f}]}{G_{f} + (1 - 2\nu_{f})G_{m}} \]  
\( (11) \)

In the debonding region, frictional slip occurs between the fiber and matrix, and the Coulomb friction law for a constant coefficient of friction, \( \mu \), governs the stress transfer.

An interfacial frictional stress, \( \tau_{fr} \), is obtained as
\[ \tau_{fr} = -\mu \left( \frac{\alpha_{f} \sigma_{f} - \nu_{m} \sigma_{m}(a,z)}{\alpha(1 - \nu_{f}) + 1 + \nu_{m} + 2\nu} + q_{th} \right) \]  
\( (12) \)

and the matrix-shear stress, \( \tau_{m}^{c} \), is expressed as
\[ \tau_{m}^{c} = G_{m} \frac{\partial \sigma_{m}(a,z)}{\partial r} = \frac{a}{r} \tau_{i} \]  
\( (13) \)

Therefore, combining Eqs. (8)–(13) yields an expression of \( \tau_{fr} \)
\[ \tau_{fr} = \frac{a}{2} P_{1} Q e^{-Qz} \]  
\( (14) \)

where:
\[ P_{1} = \frac{2b^{2} \sigma_{f} \nu_{m} \ln(b/a) - q_{th} m_{1} m_{3}}{2m_{2} a^{2} \nu_{m}(1 + \nu_{m})[\ln(b/a)]^{2}} \]
\[ P_{2} = \frac{2a^{2} \nu_{m} \ln(b/a) + \alpha_{f} \nu_{m} m_{3}}{2m_{2} a^{2} \nu_{m}(1 + \nu_{m})[\ln(b/a)]^{2}} \]
\[ Q = \frac{1}{2} P_{1} - \frac{1}{2} P_{2} + \sqrt{P_{1}^{2} + 4P_{2}} \]
\[ P_{3} = \frac{m_{1} m_{3} - 3m_{2} \nu_{m}^{2}}{4m_{2} a \nu_{m}(1 + \nu_{m})[\ln(b/a)]^{2}} \]

and where:
\[ m_{1} = \alpha(1 - \nu_{f}) + 1 + \nu_{m} + 2\nu \]
\[ m_{2} = 2b^{2} \ln(b/a) - b^{2} + a^{2} \]
\[ m_{3} = b^{2} - 2a^{2} \ln(b/a) + 4m_{2} \ln(b/a) \]

Since radial and circumferential stresses have to be neglected and \( e^{-Qz} \approx 1 \), \( \tau_{fr} \) is approximated and rewritten as
\[ \tau_{fr} \approx A \sigma_{f} + B \]  
\( (15) \)

where:
\[ A = \frac{ab^{2} Q(\alpha + \gamma)}{2a^{2} P_{2} m_{2} (1 + \gamma)(1 + \nu_{m})[\ln(b/a)]^{2}} \]
\[ B = -\frac{ab Q_{th} m_{3}}{4a^{2} P_{2} m_{2} \nu_{m}(1 + \nu_{m})[\ln(b/a)]^{2}} \]

The axial and shear stresses in the fiber and matrix are obtained for the debonding region.
\[ \sigma_j^* = \frac{2}{a} \tau_j z, \quad \tau_j^* = -\tau_j \]

(19)

\[ \sigma_m^* = \frac{M}{\rho_m} \left[ \frac{a (r^2 + b^2)}{2I_1} \right] + \left[ \frac{r}{\beta_1 \ln(b/a)} \left( \sigma_{j,\infty} - \sigma_j^* \right) \right] \]

\[ + \left( \frac{r}{\beta_1 \ln(b/a)} \left( \sigma_{j,\infty} - \sigma_j^* \right) \right] \]

\[ \tau_m^* = \frac{a}{r} \tau_j \]

(20)

where

\[ \beta_1 = (1 + \gamma) - \frac{1}{4 \ln(b/a)} \]

(21)

4.2 Bonding region

Since the interfacial shear stress is equal to \( \tau_{ym} \) in the plastic region,

\[ \tau_i = \tau_{ym} \]

(22)

Therefore, the axial and shear stresses in the fiber and matrix are obtained for the plastic region

\[ \sigma_j^* = \sigma_{fd}^* + \frac{2 \tau_{ym}}{a} (z - L_d) \]

(23)

\[ \sigma_m^* = \alpha \sigma_j^* + \frac{(r + \gamma) \ln(r/a)}{\rho_m \sqrt{b^2 \ln(b/a)}} \left[ \sigma_{j,\infty} - \sigma_j^* \right] \]

(24)

\[ \tau_j^* = \frac{r}{a} \tau_{ym}, \quad \tau_m^* = \tau_{ym} (a \leq r \leq r_p) \]

(25)

where:

\[ \sigma_{fd}^* = \frac{2 \tau_{j} L_d}{a}, \quad \beta_2 = \frac{(r + \gamma)}{\beta_1 \rho_m (1 + \nu_m) \ln(b/a)} \]

(26)

Combining Eqs. (8), (9) and (13) yields a second-order differential equation for the fiber axial stress

\[ \frac{d^2 \sigma_j^*}{dz^2} - \beta_2 \sigma_j^* = \beta_2 \sigma_{j,\infty} \]

(27)

Since the interfacial shear stress is equal to \( \tau_{ym} \) at \( z = z_p \), we obtain the interfacial shear stress and fiber axial stress for the elastic region

\[ \tau_i = \tau_{ym} e^{-\sqrt{\beta_2 (z - L_d)}} \]

(28)

\[ \sigma_j^* = \sigma_{j,\infty} - \frac{2 \tau_{ym}}{a} e^{-\sqrt{\beta_2 (z - L_d)}} \]

(29)

Therefore, the remainder of the stresses is obtained as

\[ \sigma_m^* = \alpha \sigma_j^* + \frac{2 \tau_{ym} (r + \gamma) \ln(r/a)}{\rho_m \sqrt{b^2 \ln(b/a)}} \]

\[ e^{-\sqrt{\beta_2 (z - L_d)}} \]

(30)

\[ \tau_j^* = \frac{r}{a} \tau_{ym} e^{-\sqrt{\beta_2 (z - L_d)}}, \quad \tau_m^* = \frac{a}{r} \tau_{ym} e^{-\sqrt{\beta_2 (z - L_d)}} \]

(31)

The fiber axial stress is continuous at \( z = z_p \). Using Eqs. (23) and (29), we obtain

\[ z_p = L_d + \frac{r}{2 \tau_{ym}} (2 \sigma_{j,\infty} - \sigma_{fd}) - \frac{1}{\sqrt{\beta_2}} \]

(32)

The matrix axial displacement is also continuous at \( z = z_p \). Using Eqs. (24) and (30), a matrix shear strain is obtained for the plastic region

\[ \gamma_m = \frac{(r + \gamma)}{r E_m \beta_1 \ln(b/a)} \left[ \frac{\tau_{ym}}{a} \left( z - z_p \right) + \frac{2 \tau_{ym}}{a} \right] \]

\[ \left( \sigma_{j,\infty} - \sigma_{fd} + \frac{2}{a} \tau_{ym} L_d \right) \]

(33)

The matrix shear strain is equal to \( \tau_{ym}/G_m \) at \( r = r_p \). We have finally

\[ r_p = \frac{G_m (r + \gamma)}{E_m \tau_{ym} \beta_1 \ln(b/a)} \left[ \frac{\tau_{ym}}{a} \left( z - z_p \right) + \frac{2 \tau_{ym}}{a} \right] \]

\[ \left( \sigma_{j,\infty} - \sigma_{fd} + \frac{2}{a} \tau_{ym} L_d \right) \]

(34)

Figure 3 shows the relationship between \( r_p \) normalized by fiber radius and distance from the interfacial debonding tip at 1.5 and 2.5% applied strain.

As we will mention below, a quantitative evaluation of the interfacial property is significantly depending on the value of \( \Gamma_i \). Thus, we have to confirm the validity of the present shear-lag model because the value of \( \Gamma_i \) varies along with the stress distribution obtained from a shear-lag model. To confirm the validity of the present model, we compared the present model with our previous experimental result against a distribution of the fiber axial strain as presented in Fig. 4. The experimental plots were obtained from fragmentation test using a Micro-Raman Spectroscopy (MRS) with a specimen constituted from carbon fiber and epoxy resin. According to Fig. 4, the theoretical distribution shows a good agreement with the experimental. Therefore, the present shear-lag model gives a sufficiently appropriate stress distribution.

Using \( z_p \) and \( r_p \), the plastic energy dissipation,
\[ U_{plastic}^m, \] is written as
\[ U_{plastic}^m = \int_a^b \left[ \int_{y_m}^{\infty} \frac{\tau_m \left( \gamma_m - \frac{\tau_m}{G_m} \right) dz}{2\pi r dr} \right] (35) \]

A problem with stress distributions obtained from the shear-lag equation is that they depend on an effective fiber volume fraction. Several definitions of the matrix effective radius were suggested\(^{(1),(6)}\). We consider the matrix effective radius, \( b \), is in proportion to the applied stress. Therefore, \( b \) is expressed as
\[ b = \left[ 1 + C \left( \frac{\sigma_{f\infty}}{E_f} \right) \right] \cdot a \quad (36) \]
where \( C \) depends on \( G_m/G_f \) and \( C = 9.10 \times 10^2 \) in this research.

5. Experimental

5.1 Materials and test procedure

The constituents of a test specimen were an ECR-glass fiber and vinylester resin. The geometry of a test specimen is shown in Fig. 5. A pre-load was applied to each fiber to compensate for a compressive strain induced by a thermal residual stress when fabricating the specimen. Curing lasted 3 h at room temperature, followed by 2 h at 80 °C, and slow cooling to room temperature. The compounding ratio of the vinylester resin and the mechanical properties of the fiber and matrix are listed in Tables 1 and 2, respectively.

Fragmentation tests were performed with a compact-tensile machine at a constant crosshead speed of 0.05 mm/min at room temperature in air, monitored by optical microscope. We recorded the applied strain at which each fiber break occurred, and took a photograph in the vicinity of a fiber-break point. Debonding length and matrix-crack radius were measured from the digital image (Fig. 1). Besides that, we decreased the fiber strength 60% by heat cleaning at 625 °C maintaining the same surface condition, and performed the fragmentation test using a specimen in which the heat-cleaned fiber is embedded.

5.2 Results

In the fragmentation test, some fiber breaks were occurred with both the interfacial debonding and matrix crack as shown in Fig. 1, and the others were done with only the interfacial debonding as shown in Fig. 6. A series of plots showing the dependence between the initial debonding length and the fiber stress at which a fiber break occurred is presented in Fig. 7. As seen in Fig. 7, the fiber breaks of the as-received occur at higher strain, and the debonding length of the as-received generally tends to be longer.

### Table 1 Properties of vinylester resin

<table>
<thead>
<tr>
<th>Chemicals</th>
<th>Compounding ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active component: Ripoxy R802</td>
<td>100</td>
</tr>
<tr>
<td>Curing agent: Methyl ethyl ketone peroxide</td>
<td>0.9</td>
</tr>
<tr>
<td>Accelerator: Cobalt naphthenate</td>
<td>0.3</td>
</tr>
</tbody>
</table>

### Table 2 Mechanical properties of the fiber and matrix

<table>
<thead>
<tr>
<th></th>
<th>ECR-glass</th>
<th>Vinylester</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus ( E ) (GPa)</td>
<td>76.0</td>
<td>3.00</td>
</tr>
<tr>
<td>Poisson’s ratio ( \nu )</td>
<td>0.14</td>
<td>0.34</td>
</tr>
<tr>
<td>CTE c (K)</td>
<td>5.60 x 10^-6</td>
<td>6.50 x 10^-6</td>
</tr>
<tr>
<td>Diameter (μm)</td>
<td>23.0</td>
<td>-</td>
</tr>
<tr>
<td>Tensile strength (GPa)</td>
<td>2.40</td>
<td>-</td>
</tr>
<tr>
<td>Gauge length (mm)</td>
<td>25.0</td>
<td>-</td>
</tr>
<tr>
<td>Yielding stress (MPa)</td>
<td>-</td>
<td>65.0</td>
</tr>
<tr>
<td>Fracture energy ( f ) (J/m²)</td>
<td>10.0</td>
<td>2.26 x 10²</td>
</tr>
</tbody>
</table>

Fig. 5 Size and dimension of specimen

Fig. 6 Photograph in the vicinity of a fiber-break point of ECR glass/vinyleester composite

Fig. 7 Plots of the dependence between the initial debonding length and the applied strain
6. Discussion

6.1 Comparison of interfacial energy

A relationship between the fiber strength and the interfacial energy derived from an elastic analysis (Eq. (4)) and the present analysis (Eq. (7)) is shown in Fig. 8. In the elastic analysis, the stress distribution for the bonding region is expressed as

\[ \sigma_z^e = \sigma_{f,\infty} - (\sigma_{f,\infty} - \sigma_{f,d}) \cdot e^{-\sqrt{\beta_2} (z - L_d)} \]  
(37)

\[ \tau_i^e = \frac{a}{2} \sqrt{\beta_2 (\sigma_{f,\infty} - \sigma_{f,d})} \cdot e^{-\sqrt{\beta_2} (z - L_d)} \]  
(38)

\[ \tau_{r,z}^m = \frac{a}{r} \tau_i, \quad \tau_{r,z}^f = \frac{r}{a} \tau_i \]  
(39)

\[ \sigma^e_m = a \sigma^e_f + \frac{2(\sigma_{f,\infty} - \sigma_{f,d})(\alpha + \gamma) \ln(r/a)}{\alpha \beta_1 \ln(b/a)} \cdot e^{-\sqrt{\beta_2} (z - L_d)} \]  
(40)

Figure 8 shows that the value of \( \Gamma_i \) is quite different between Eqs. (4) and (7), and also shows that as the fiber strength becomes higher the difference becomes larger. Therefore, the following results are confirmed: the plastic deformation has a significant influence on the interfacial energy, and the influence becomes more significant as the strain at which a fiber break occurs increases because the increase of the applied strain expands the plastic region (Fig. 3).

Considering \( \Gamma_m = 226 \text{J/m}^2 \), the value of \( \Gamma_i \) derived from Eq. (4) is huge, and so invalid to evaluate an initiation of the interfacial debonding, and the value of \( \Gamma_i \) obtained from the present analysis is valid. In addition to that, \( \Gamma_i \) obtained from the present analysis is constant without reference to the fiber strength, that is, the amount of the released potential energy accompanying a fiber break. Therefore, the initiation of the interfacial debonding is evaluated quantitatively by means of the value of \( \Gamma_i \) derived from the present analysis because each condition of the interfacial adhesion is excepted to have its own value of \( \Gamma_i \), i.e., the value of \( \Gamma_i \) is not excepted to vary following with changing of the fiber strength for the same surface condition.

6.2 Validity of present model

To further assess the validity of the present model, the fragmentation tests with another condition were performed, and the interfacial energy was calculated. The condition was that a pre-load was increased to decrease apparent fiber strength and the apparent strength was 1.9 GPa.

The relationship between the fiber strength and the interfacial energy is shown in Fig. 9. Obviously, Fig. 9 shows the same tendency as Fig. 8. According to that, we finally conclude that the initiation of the interfacial debonding is evaluated quantitatively by means of the value of \( \Gamma_i \) obtained from the present energy balance method.

7. Concluding Remarks

The present paper proposes an energy balance method considering an energy dissipation of the plastic deformation for the analysis of the interfacial energy. The fragmentation test was performed, varying the fiber strength. During the tests, the plastic deformation around the interfacial debonding was observed. Some fiber breaks were occurred with the debonding and matrix crack, and the others were only with the debonding. The plastic region expands according to the increase of the applied strain, and naturally the energy dissipation of the plastic deformation increases. We concluded that the present energy balance method gives a constant value of the interfacial energy independent of the fiber strength for the same surface condition and the interfacial adhesion is evaluated quantitatively by the interfacial energy obtained from the present analysis.

References

(3) Wagner, H.D., Nairn, J.A. and Detassis, M., Toughness


