Energy Release Rate for Fiber Reinforced Polymer Composite

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Abstract: *An experimental investigation using drag-out tensile test to calculate the interfacial shear strength for different embedded lengths and radius of Kevlar -49, carbon and ultra high polyethylene fibers reinforced epoxy matrix , the energy release rate calculated by using Nairn model . The energy release rate increase as the embedded fiber length increase and also for fiber radius for perfect adhesion , for specimens with bubbles at interface which seems to reduce the fracture toughness the energy release rate be less than specimens with perfect adhesion , the thermal stress and friction forces were included in the energy release rate in Kevlar-49 and carbon reinforced epoxy the interfacial shear force due to friction part decrease while in solid ultra high polyethylene the interfacial shear force due to friction part increase.*

Keywords: *Energy release rate , Crack , Drag-out , Interfacial shear stress*

I. Introduction

The efficiency of fiber-reinforced composites is often controlled by the properties of the fiber-matrix interface. Good interfacial bonding (or perfect adhesion), to ensure load transfer from matrix to reinforced fiber, is a primary requirement for effective use of reinforcement properties. Thus, a fundamental understanding of interfacial properties and a quantitative characterization of interfacial adhesion strength can help in evaluating the mechanical behavior and capabilities of composite materials [1,2]. A large number of analytical techniques have been developed for understanding interfacial adhesion of Kevlar and carbon fibers reinforced epoxy matrix such as drag-out adhesion test of U-shaped single fiber specimen , the interfacial shear strength which is an interfacial parameter calculated using Kelly-Tyson as analytical model [3] and the drag-out micromechanical test of U-shaped specimen [4] to measure the maximum pull-out force or peak force from force-displacement curve and also the energy release rate include the thermal stress and fraction force by Nairn[2].

II. Theory

The elemental forces balance in fiber reinforce matrix shown in Fig (1).
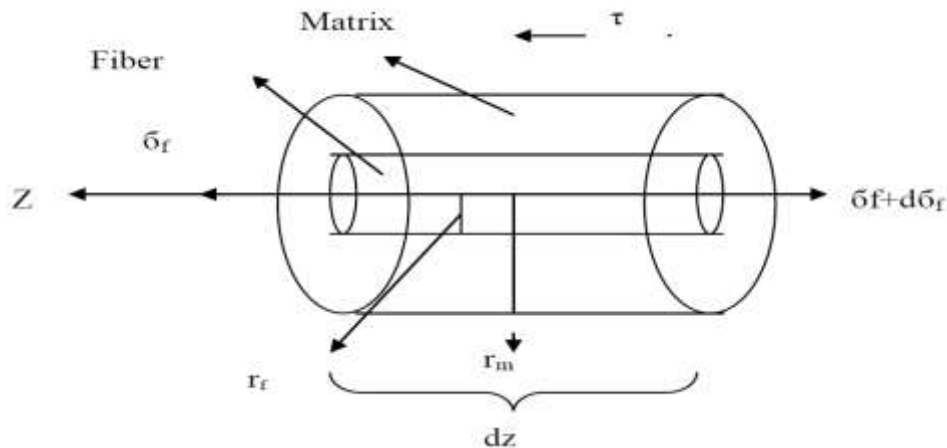

Fig 1: Directions of shear stresses

Where :
σ_f = stress applied to the fiber
r_f=fiber radius
r_m=matrix radius
τ=shear stress
dz=element length and le is the fiber embedded length which equal to
the specimen length

$$\sigma_f(\pi r_f{}^2) + \tau(2\pi r_f\, dz) - \pi r_f{}^2(\sigma_f + d\sigma_f) = 0$$

$$\frac{d\sigma_f}{dz} = \frac{2}{r_f}\tau$$

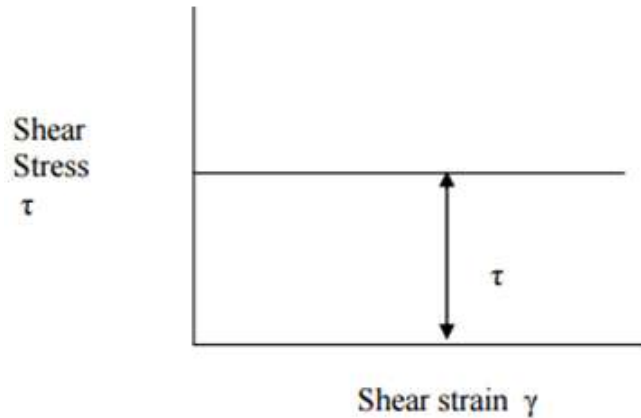$$\int_{\sigma_o}^{\sigma_f} d\sigma_f = \int_0^1 \frac{2}{r_f}\tau\, dz$$

Fig (2) Average shear stress

If we neglected the stress transferred at the end of fiber ($\sigma_0 = 0$ at z=0)

$$\sigma_f = \frac{2}{r_f}\int_0^1 \tau\, dz \qquad \text{-------------------- 1}$$

To solve the integral we must know τ as function of Z, Kelly-Tyson model [3] assumed the matrix to be rigid-plastic Fig (2) so equation (1) be

$$\sigma_f = \frac{2\tau}{r_f}\int_0^1 dz$$

$$\sigma_f = \frac{2\tau l_e}{r_f}$$

$$\tau = \frac{r_f \sigma_f}{2 l_e} \qquad \text{------------------ 2}$$

$$\sigma_f = \frac{F_p}{\pi r_f{}^2} \qquad \text{------------------ 3}$$

Substitute equation (3) in equation (2) Kelly-Tyson model [4]

$$\tau_{ifss} = \frac{F_p}{2\pi r_f l_e} \qquad \text{------------------ 4}$$

The energy release rate by Nairn include thermal stress and friction force given [8]:

$$G_\infty(a) = \frac{r_f}{2}\left[C_{33s}(\sigma_d - ka)^2 + D_{3s}(2\sigma_d - k(2a + \frac{1}{\beta})\Delta T + (\frac{D_3^2}{C_{33}} + \frac{V_m(\alpha_T - \alpha_m)^2}{V_f A_0})\Delta T^2 \right]$$

Where:
β is the shear-lag parameter and defined as: [6,7].

$$\beta^2 = \frac{2}{r_1^2 E_A E_m} \left[\frac{E_A \upsilon_f + E_m \upsilon_m}{\frac{V_m}{4G_A} + \frac{1}{2G_m}\left(\frac{1}{V_m}\ln\frac{1}{V_f} - 1 - \frac{V_f}{2}\right)} \right]$$

$\sigma_d =$ The axial stress at peak force in force- displacement curve

K=the fractional stress transfer $= \dfrac{2\tau_f}{r_f}$ and $\tau_f = \dfrac{F_r}{2\pi r_f l_e}$

$\Delta T =$ the different between stress free temperature and the specimen temperature
The volume fraction of fiber V_f and matrix V_m defined in the reference [5, 8]
And other constant defined in reference [8]
Fiber and matrix properties listed in table (1) and table (2)

Table 1: The properties of fibers:

Properties	Carbon fiber AS4	Kevlar fiber
Tensile Modulus (E_A)(Gpa)	380	130
Transverse modulus (E_T)(Gpa)	40	10
Axial shear modulus (G_A)(Gpa)	20	15
Axial poisson ratio $\left(\upsilon_A\right)$	0.22	0.2
Transverse poisson ratio $\left(\upsilon_T\right)$	0.25	0.35
Axial coefficient of thermal expansion $\left(\alpha_A\right)$ $10^{-6}c^{-1}$	-0.7	-2
Transverse coefficient of thermal expansion $\left(\alpha_T\right)$ $10^{-6}c^{-1}$	10	-60

Table 2: The properties of matrix

Properties	Epoxy
Tensile modulus (E_m)(Gpa)	5
Axial shear modulus (G_m) (Gpa)	1.23
Axial poisons ratio (υ_m)	0.35
Axial coefficient of thermal expansion(α_m) $10^{-6}c^{-1}$	50

III. Specimen preparation

A polysiloxane mold of different embedded lengths fiber (3.09mm,4.12mm,5.14mm) used to get U-shape specimen as shown in Fig. 3 .Three kinds of fiber A kevlar-49, carbon fiber with diameters (0.22mm, 0.34mm,o.43mm) and ultra high polyethylene fiber (UHPE) with diameters (0.45mm) used to reinforced epoxy matrix cured at room temperature for six days in polysiloxane mold before tensile test by (Microcomputer Controlled electronic Universal Testing machine model WDW-5E).

Fig (3) A: Polysiloxane U-shaped mold

Fig (3) B: U-shaped drag-out specimen

IV. Results and discussion

The force vs. displacement curves from drag-out test of specimens shown in Fig (4),(5),(6),(7),(8),(9)
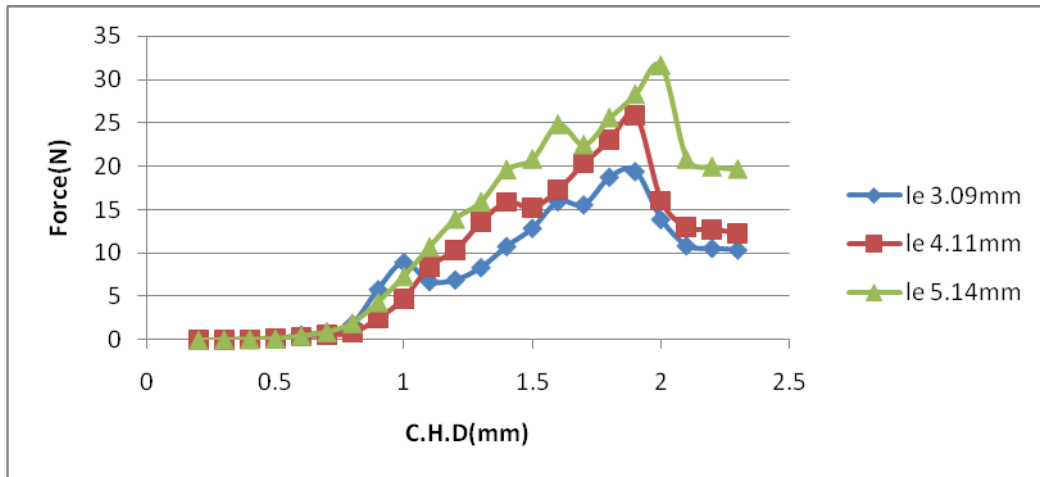

Fig (4) the drag-out force vs. cross head displacement curves for epoxy-carbon fiber post cure at 25°C of diameter (0.22mm).
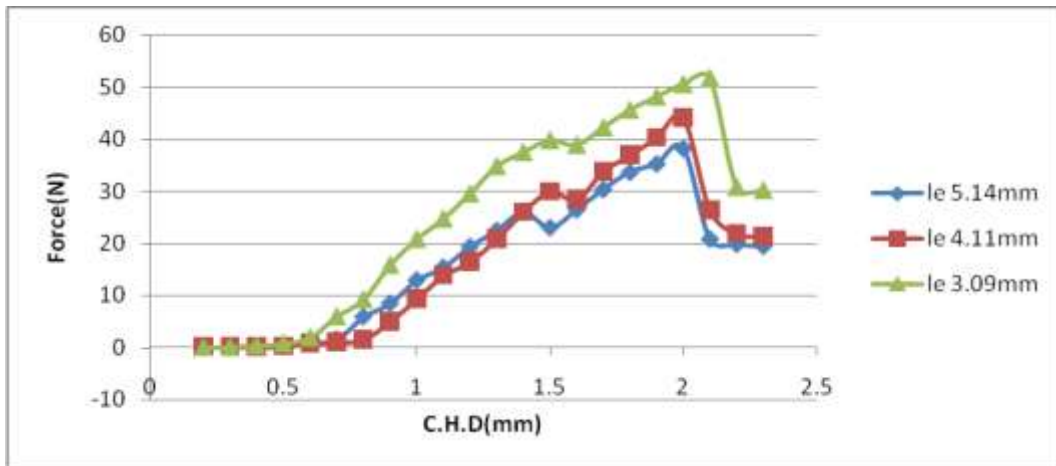

Fig (5) the drag-out force vs. cross head displacement curves for epoxy-carbon fiber post cure at 25°C of diameter (0.34mm).
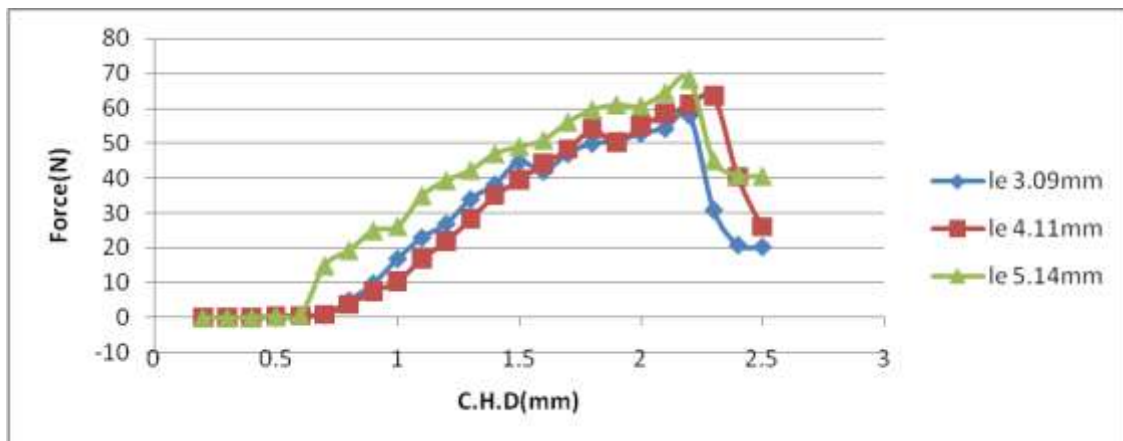

Fig (6) the drag-out force vs. cross head displacement curves for epoxy-carbon fiber post cure at 25°C of diameter (0.43mm).
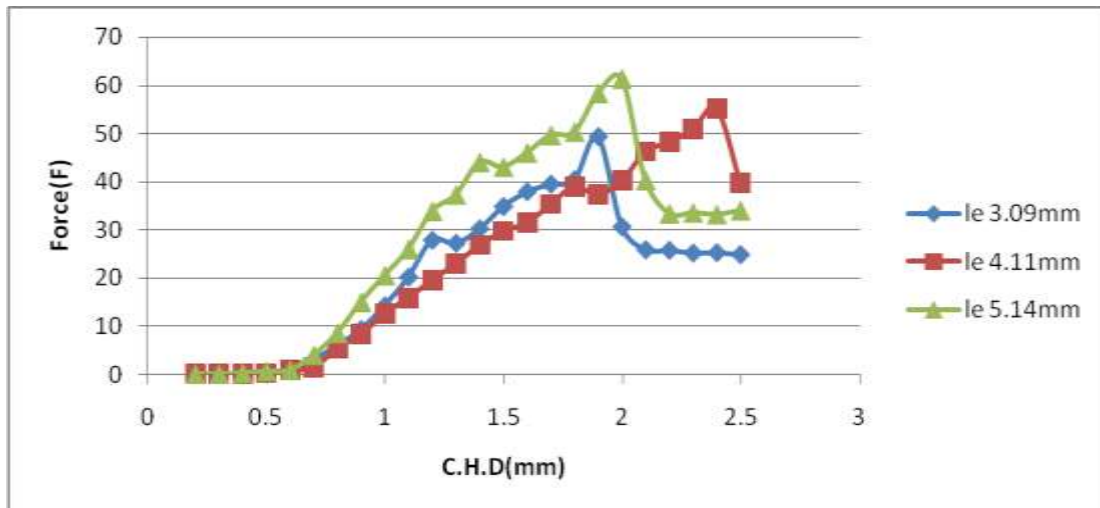
Fig (7) the drag-out force vs. cross head displacement curves for epoxy-Kevlar fiber post cure at 25°C of diameter (0.22mm).
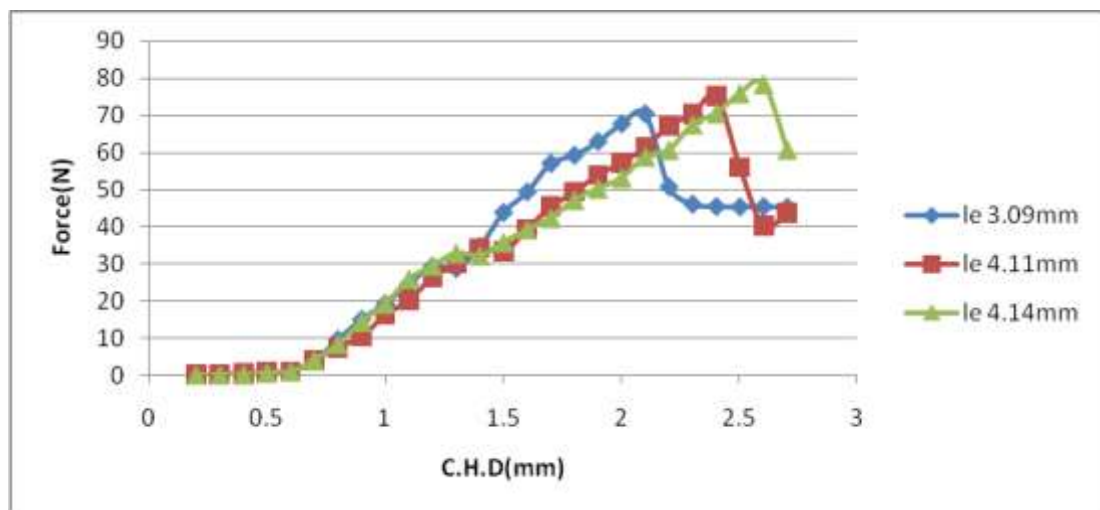

Fig (8) the drag-out force vs. cross head displacement curves for epoxy-Kevlar fiber post cure at 25°C of diameter (0.34mm).
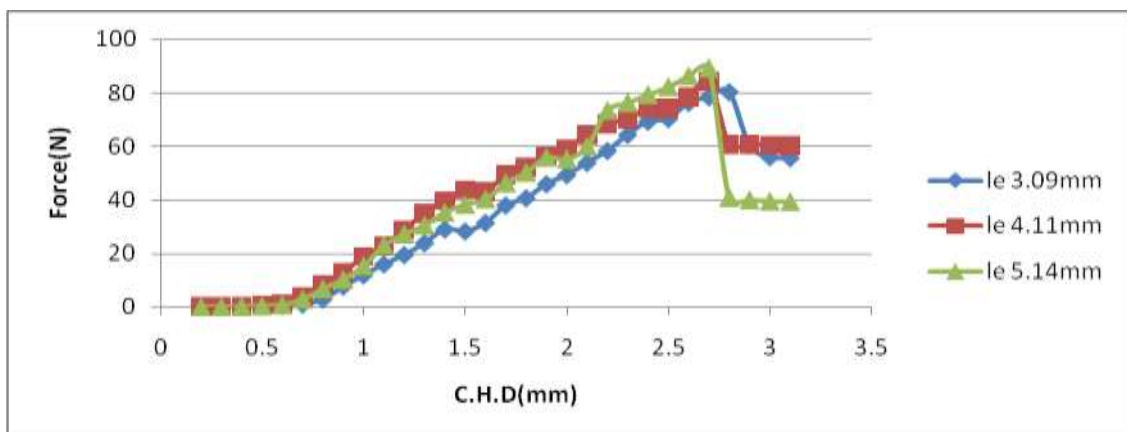

Fig (9) the drag-out force vs. cross head displacement curves for epoxy-Kevlar fiber post cure at 25°C of diameter (0.43mm).
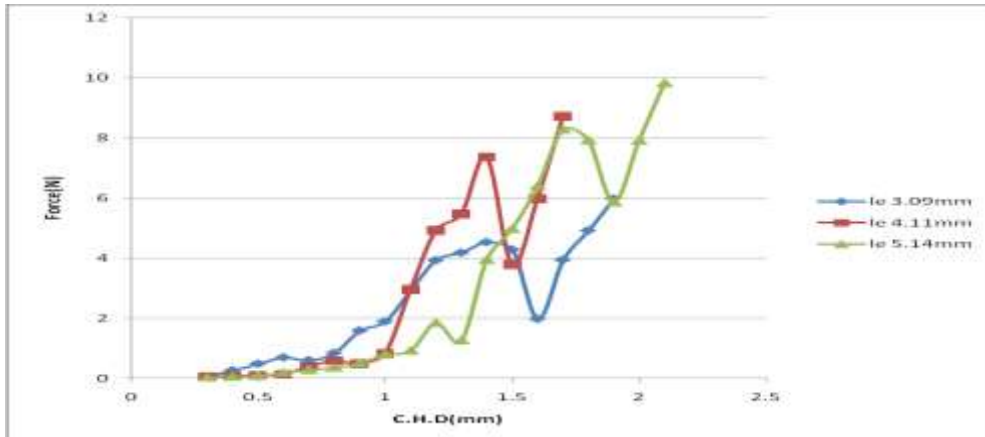
Fig (10) the drag-out force vs. cross head displacement curves for epoxy- polyethylene fiber post cure at 25°C of diameter (0.45mm).

The energy release rate G(a) for an interfacial debond crack by Nairn model, the energy release rate is an indication for crack propagation at interface. Fig(4) shown the peak force (full debound) for different for embedded fiber lengths and as the fiber length increase the peak force and then the energy release rate increased as surface area between fiber and matrix be larger and then the bound strength increase.

The energy release rate increase when fiber diameter and embedded length increase as in Fig (11) (12)
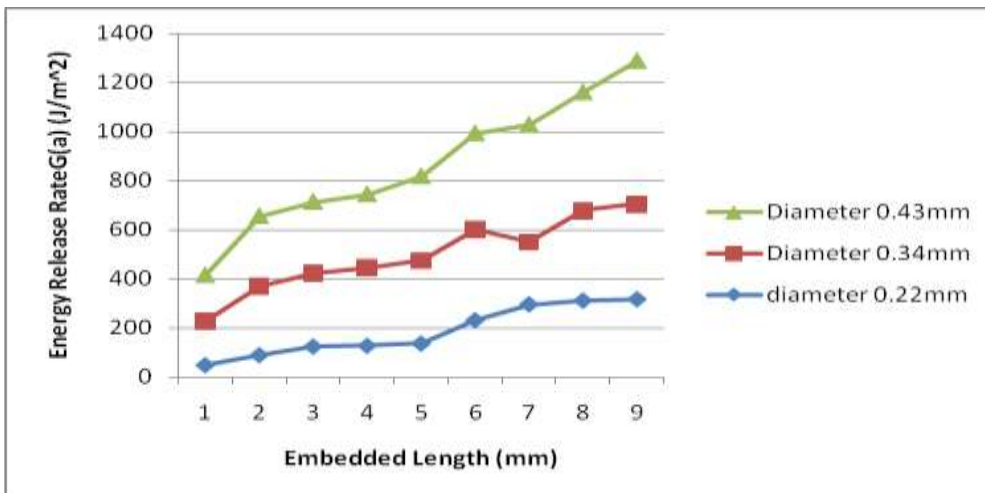

Fig (11) Energy release rate for Kevlar fiber at three diameters
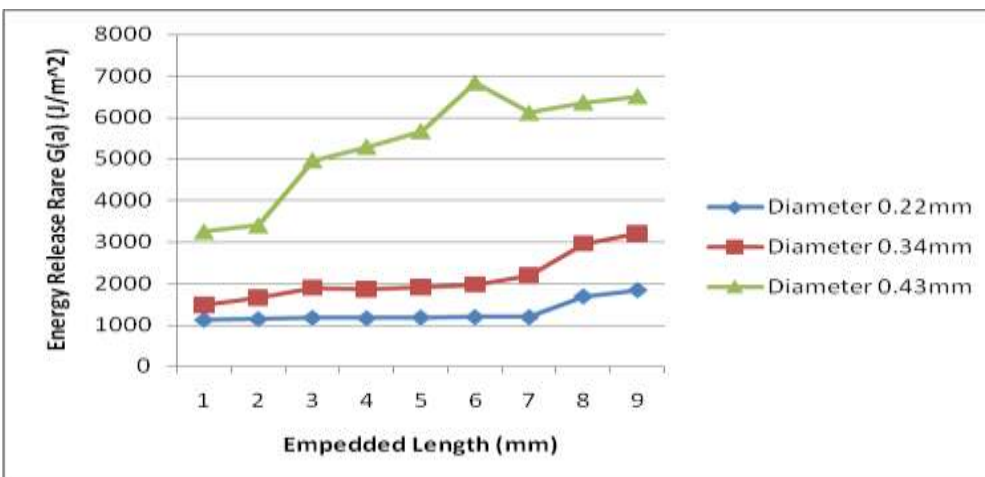

Fig (12) Energy release rate for carbon fiber at three diameters

The energy release rate is increase when the surface area of the fiber increase that is to mean the adhesion area between fiber and matrix increase (perfect adhesion) but there are some abnormal behavior in samples which shown a decrease in the in energy release rate when increasing the diameter that can be explained this adhesion between the fiber and the matrix is imperfect adhesion for several reasons due to the presence of bubbles between fiber and matrix or a fiber containing filaments.

The energy release rate for polyethylene fiber are very low in compared with the carbon fiber and Kevlar fiber as in Fig (10) because of the poor adhesion of ultra high polyethylene (UHPE) fiber with epoxy resin due to its surface structure characteristics it have low friction coefficient, highly resistant to corrosive chemicals, the surface roughness polyethylene fiber, low surface energy.

V. Conclusion

1. Nairn model include interfacial shear strength, thermal stress and friction.
2. The increasing in the embedded length of the fiber and diameter, which leads to increased adhesion area does not mean increasing of the energy released rate, for several reasons due to the presence of bubbles between fiber and matrix or a fiber containing filaments (not perfect adhesion)
3. Using nano fiber reinforce polymer matrix the adhesion between fiber and matrix will be perfect.
4. Drag-out test is more flexible than pull-out and microbond tests.
5. The high difference between the values of frictionless energy release rate and the values of energy release rate indicated the importance of friction effect. at the friction part of all dag-out force-displacement curves there are two kinds, slip-hardening, if the surface of matrix is more hard than fiber surface caused surface fiber abrasion and the friction force would increase over peak force, the second kind was slip-soften occurred when the surface of fiber is more hard than matrix surface and the friction force would be less than the peak force.

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