⊙ 研究論文

Fracture Behavior of Advanced Composite Material

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尖端複合材料의 破壞擧動

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Key words : Fracture Behavior(파괴거동), Composite Material(복합재료), Static Strength(정적강도), Fatigue Strength(피로강도), Successive Observation(연속관찰), Stress Concentration(응력집중), Linear Notch Mechanics(선형노치역학)

요 약

기계나 구조물 파괴의 대부분은 노치부를 기점으로 하여 발생하기 때문에 첨단복합재료를 노치부재로서 안전하면서도 경제적으로 사용하기 위해서는 각종 조건하에 있어서 강도특성을 명확히 하는 것은 대단히 중요하다.

본 연구에서는 노치를 갖는 복합재료를 이용하여 각종조건하에서 강도특성평가실험을 행하였으며, 얻어진 결과를 종합하면 다음과 같다.

(1) 첨단복합재료 노치재는 試驗片의 幾何學的 形狀과는 관계없이 노치반경 ρ만에 의해 결정되는 최대탄성응력 σ_{max} 일정의 條件下에서 破壞된다.

(2) 破斷時 最小斷面에서의 공칭응력 σ_c와 응력집중계수 K_t와의 관계에 있어서, σ_c의 값이 K_t의 增大와 더불어 떨어지고 있는 부분과, K_t와 관계없이 거의 일정하게 되고 있는 부분으로 나누어지는 現象은 노치재의 回轉굽힘 또는 引張壓縮疲勞에서 보여지는 現象과 外觀上 對應하고 있다. 즉, 정적파괴와 피로파괴는 파괴의 양상이 비슷하다.

(3) PEN수지단체의 경우, 피로균열발생은 점발생적 피로균열이 최대탄성응력에 의해 지배되며, 노치에 만감하며, 균열전파수명은 전수명에 비해 상당히 짧다.

(4) 단탄소섬유강화복합재료의 경우, 피로균열은 섬유端에 응력이 집중하기 때문에 일반적으로 섬유端에서 아주 빠른 시기에 발생하지만, 섬유가 피로균열진전에 대해 방해물로 작용하기때문에 아주 천천히 전파한다.

(5) 短炭素纖維는 피로균열발생에 대해서는 負의 강화작용 전수명의 극히 초기단계에 피로균열 발생을, 피로균열전파에 대해서는 正의 강화작용을 한다.

(6) 단탄소섬유를 PEN에 강화함으로 인해 정적강도 보다 피로강도에 더 큰 강화효과를 초래했으

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며, 선형노치역학의 개념은 첨단복합재료의 강도평가에 대단히 유효했다.

1. Introduction

Composite materials are useful for structural applications where the high specific modulus are required. Aircraft and spacecraft are typical weight-sensitive structures in which composite materials are cost-effective[1]. For this reason, many studies on the fatigue and static fracture of continuous fiber reinforced composites have been conducted to keep structures working safely[2]. However, there are a few studies concerning the fatigue mechanism of short fiber reinforced composites[3-6] because of the complexity of fatigue phenomenon due to the source of stress concentration such as fiber end or fiber-matrix interface.

The thermoplastic resin polyethernitrile (PEN), which has excellent properties at high temperature is a crystalline polymer which possesses good environmental and chemical resistance. The studies conducted by Nisitani et al[7-8] regarding the effect of a notch on the static tensile strength of polycarbonate and polycarbonate-matrix composite has led the conclusion that the fracture development of these materials is only directly related to the elastic maximum stress, σ_{maxc}, and notch root radius, ρ. There are few studies, however, on the investigation of the static and fatigue strength characteristics of PEN and PEN-matrix composite.

In this study, the static and fatigue tests for PEN and PEN-matrix composite were carried out to investigate the static and fatigue characteristics of plain and notched specimens. The static and fatigue mechanisms were clarified through successive surface observation using the replica method and the notched fatigue strength was discussed based on linear notch mechanics.

2. Linear Notch Mechanics

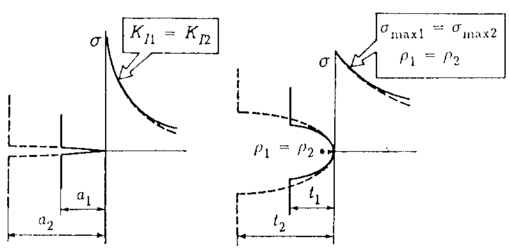
In most cases, the failure or fracture of machines and structures are brought on by the localized damage of the part where the stress concentration due to the existence of a crack or a notch occurs. On the other hand, it is well known that the elastic maximum stress σ_{max} is not enough to predict the failure or fracture. Therefore, it is very important to evaluate the severity of the part having a crack or a notch.

Concerning a crack, linear fracture mechanics[9] can play an important role to predict the fracture or yield in the neighborhood of a crack tip. That is, stress intensity factor is the effective measure of severity controlling the localized damage in a crack. However, concerning a notch, the concept corresponding to linear fracture mechanics is not discussed fully until now.

In general, a crack appears necessarily before any kind of fracture.

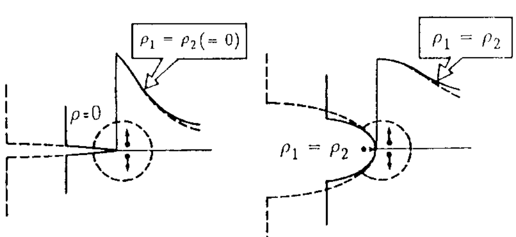
Therefore, it may be considered that linear fracture mechanics is sufficient in treating all kinds of fracture problems. However, many notch problems[12] can not be treated correctly without considering the characteristics of notches. Linear notch mechanics[10-11] should be defined as an engineering method which treats the notch problem by elastic stress fields alone. Similarly, linear fracture mechanics is defined as an engineering method which treats the crack problems by elastic stress fields alone. If the values of K_I in two cracked bodies are equal to each other, the elastic stress fields near the crack tips are equal to each other in two cracked bodies, independent of crack size or the other geometrical conditions [Fig. 1(a)]. There is a similar situation for notches. That is, if the values of the elastic maximum stress σ_{max} and notch root radius ρ in two notched bodies are equal to each other respectively, the elastic stress fields near the notch roots are equal to each other in the two notched bodies, independent of notch depth or the other geometrical conditions [Fig. 1(a), Fig. 2].

The same elastic stress fields do not necessarily assure the occurrence of the same localized damage, because the localized damage (fatigue crack initiation, brittle fracture, local yields etc.) is usually accompanied by plastic deformation and the same elastic stress fields do not necessarily assure the occurrence of the same plastic deformations(the same elastic-plastic stress fields).



K_I controls elastic stress field. σ_{max} and ρ control elastic stress field

(a) Condition for the same elastic stress fields in two cracked bodies or two notched bodies.

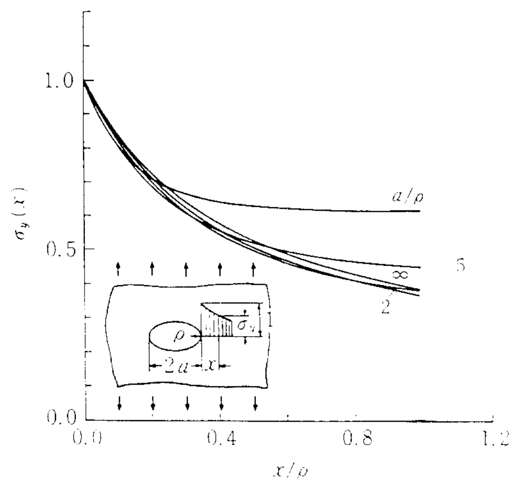


Geometric condition near crack tips controls response. Geometric condition near notch roots controls response.

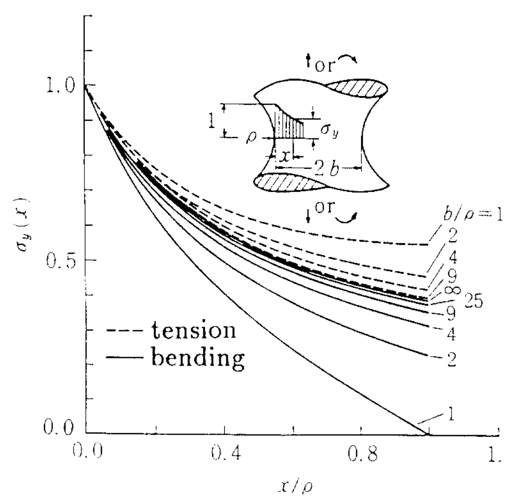
(b) Condition for the same responses against plastic deformation in two cracked bodies or two notched bodies.

Fig. 1 Same elastic stress fields and same responses in the cracked members or two notched members.

The reason why the same elastic stress fields assure the occurrence of the same localized damage is that the conditions for the same elastic stress fields include the condition for the same responses against plastic deformation, as shown in Fig. 1(b). The same responses against plastic deformation mean the occurrence of the same additional stress fields due to a given amount of plastic deformation at a given place in two cracked or two



(a) Elliptic hole



(b) Hyperboloidal notch

Fig. 2 Elastic stress field near the notch roots is mainly determined by the values of σ_{max} and ρ alone.

notched bodies. The situations are shown schematically in Fig. 1(b). The same elastic stress fields and the same responses against plastic deformation assure the occurrence of the same elastic - plastic stress fields, in two cracked bodies or in two notched bodies. The same elastic - plastic stress fields assure the occurence of the same localized damage. The interrelation of these facts is shown in Fig. 3. From the above discussion, it is concluded that

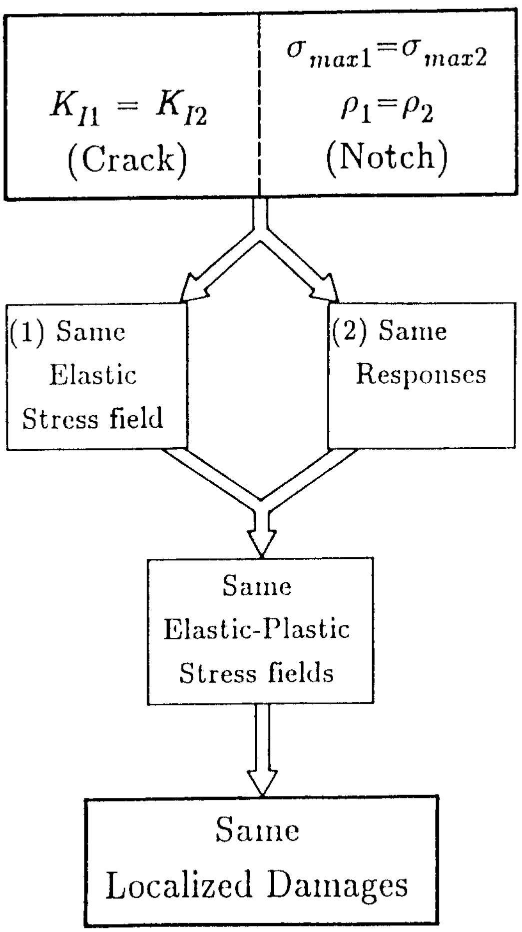


Fig. 3 Condition for the same phenomena occuring in two cracked members or two notched members.(The same elastic stress fields and equivalence of responses assure the same elastic - plastic stress fields. The same elastic - plastic stress fields assure the same phenomena in two cracked members or two notched members.)

the measure of severity controlling the localized damage is the value of K_I in a crack and the value of σ_{max} and notch root radius ρ in a notch. The former is the measure of severity in linear fracture mechanics which should be called linear crack mechanics and the latter is the measure of severity in linear notch mechanics.

That is, linear notch mechanics is defined as an engineering method which treats the notch problems by elastic stress fields(represented by σ_{max} and ρ) alone, similarly as linear crack mechanics is defined as an engineering method which treats the crack problems by elastic stress fields(represented by stress intensity factors) alone.

Based on linear crack mechanics and linear notch mechanics, the conditions for causing the same localized damage in two cracked bodies or two notched bodies are shown in Fig. 3. In this figure, only the case of mode I is treated, because the case of the other mode is similar to the case of mode I.

3. Materials and Experimental Procedure

The materials used are polyethernitrile(PEN), manufactured by Idemitsu Kosan Co. Ltd., Japan and fiber reinforced polyethernitrile (CFRPEN). The melting temperature and glass transition temperature of PEN are 340℃ and 145℃ respectively. The fiber reinforced polyethernitrile contains 15 and 30 percent by weight of randomly oriented short carbon fibers with a diameter of 7μm and a mean length of 100μm.

Photo. 1 shows the microstructure a polished CFRPEN. Fig. 4 shows the specimen configuration of plain and notched specimens. In order to detect the starting point of fracture and ob-

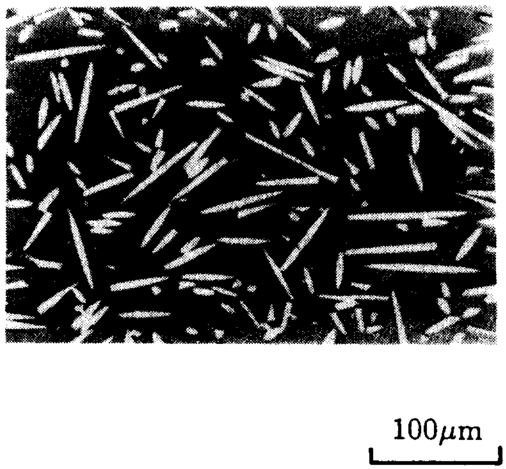
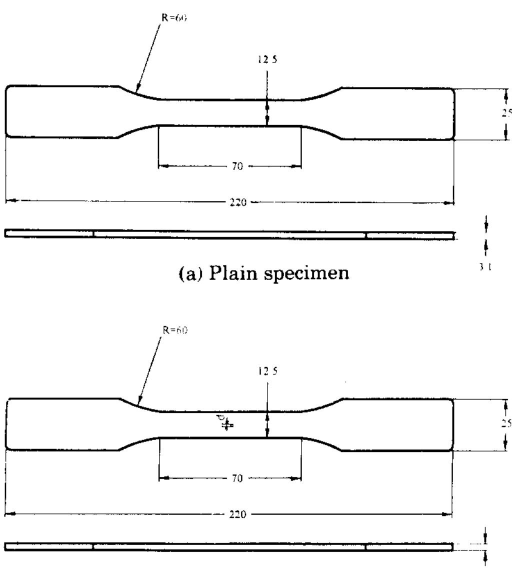


Photo. 1 Microstructure of CFRPEN



(a) Plain specimen

(b) Notched specimen

Fig. 4 Specimen configurations

serve the fatigue processes successively, all specimens were polished with fine emery paper, alumina and diamond paste, and the testing machine was stopped several times at appointed number of cycles. The plastic replicas were taken under the unloaded state. The replicas were examined with the optical microscope after coating with gold in vacuum.

Tensile tests of center notched plates for PEN and CFRPEN were carried out for four different notch root radii and two different notch depths under the conditions of constant specimen thickness. It was performed at room temperature under a constant cross head speed of 0.5mm/min.

Fatigue tests of PEN and CFRPEN notched specimens were carried out for four different small hole sizes(d=0.6, 1.1, 4 and 6mm) under the condition of constant specimen thickness. The loding condition was given by the stress ratio of R=0.05. Fatigue tests were performed at room temperature by survo pulser(EHF - FBI - IOLA type, capasity : dynamic ±1 ton, static ±1.5 ton) fatigue testing machine.

4. Results and Discussion

4. 1 Static strength of PEN and CFRPEN

Fig. 5 shows the tensile stress - strain curves of PEN(Carbon fiber=0%) and CFRPEN(Carbon fiber=15% and Carbon fiber=30%). The material property data extracted from tensile tests are shown in Table 1.

By reinforcing PEN with the short carbon fibers, the static tensile strength and the elastic

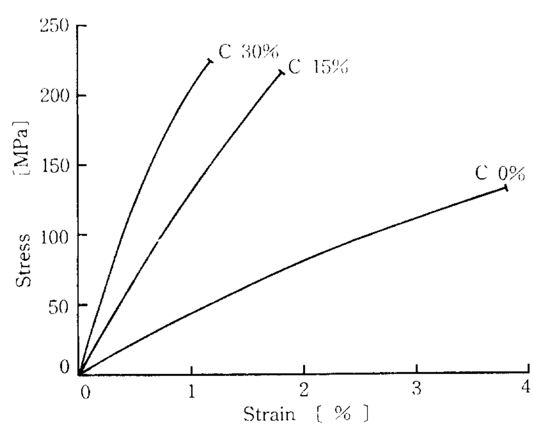


Fig. 5 Stress Strain curves of PEN and CFRPEN

Table 1 Mechanical properties

	σ_B(MPa)	E(GPa)	δ(%)
0%	132	4.4	3.8
15%	216	14.1	1.8
30%	225	25.0	1.4

σ_B : Ultimate tensile strength
E : Young's modulus
δ : Elongation

modulus of CFRPEN increases respectively, However, the elongation at fracture decreases on the contrary. This implies that by adding fibers reduces the degree of ductility in PEN.

Fig. 6 shows the relation between the stress causing brittle fracture σ_c and the stress concentration factor K_t in the PEN and CFRPEN specimens having two different notch depths and four different notch root radii. The relation of σ_c K_t are to be classified into two parts, namely, a part where σ_c decreases with increasing K_t and a part where σ_c is nearly constant independent of K_t, as shown Fig. 6.

A similar phenomenon can be seen in notched specimens under fatigue tests[13 16]. It suggests that the fracture in the notch root is not governed by the σ_c. However it is evident that the elastic maximum stresses at fracture for PEN and CFRPEN having a constant notch root radii are nearly constant, independent of the notch depths, as depicted in Fig. 7.

According to the concept of linear notch mechanics, there should be one to one correspondence between σ_{max} and 1/ρ, independent of the value of notch depth and the other geometrical conditions. Fig. 7 support it clearly. Fig. 7 show the relation between the critical elactic maximum stress, and the reciprocal of the notch root radius, 1/ρ. It can be seen from Fig. 7 that all experimental data fall approximately on a unique characteristic curve, independent of the notch depths. Therefore, it can be concluded from the above results that the occurrence of

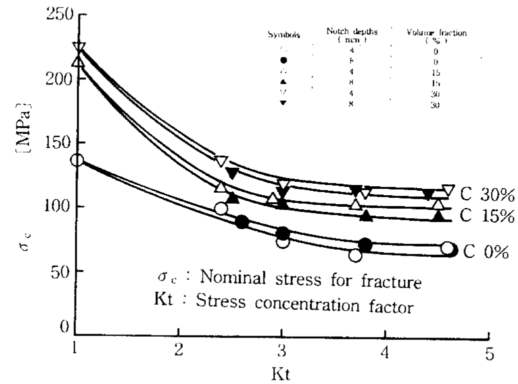


Fig. 6 Relation between the stress for causing brittle fracture, σ_c, and the stress concentration factor, K_t.

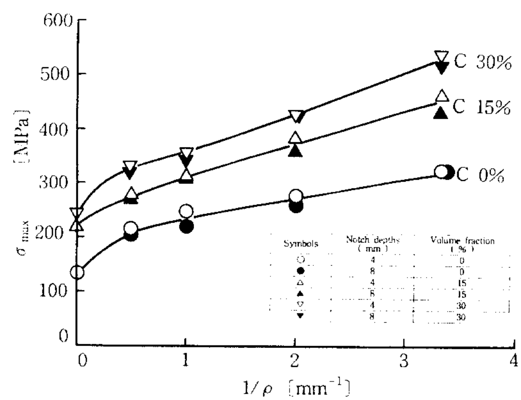


Fig. 7 Relation between the critical elastic maximum stress, σ_{max} and 1/ρ, the reciprocal of the notch root radius, 1/ρ.

fracture in PEN and CFRPEN is only related to the critical elastic maximum stress σ_{max} and the notch root radius ρ alone, independent of the other geometrical conditions. By using Fig. 7 as the master curves for the brittle frature of these materials, we can predict the limiting stress for the brittle fracture an arbitrarily shaped plate specimen having the same thickness. This proves the usefulness of linear notch mechanics.

4.2 Fatigue strength of CFRPEN in comparison to PEN

Fig. 8 shows the S - N curves of the fatigue tests of PEN and CFRPEN(Carbon fiber = 30%) including plain specimens and specimens with a notch of 1.1mm in diameter. As shown in Fig. 6, the fatigue strength of CFRPEN is approximately 2 times of that of PEN in both plain and notched specimens. That is, the ratio of the fatigue strength of matrix resin to the one of CFRPEN is a little higher than the ratio of the tensile strength.

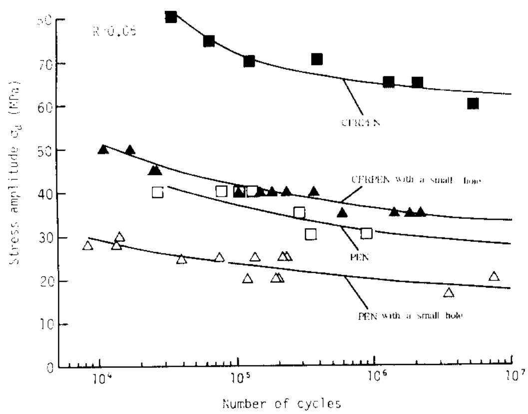


Fig. 8 Comparison of S-N curves of PEN and CFRPEN plates

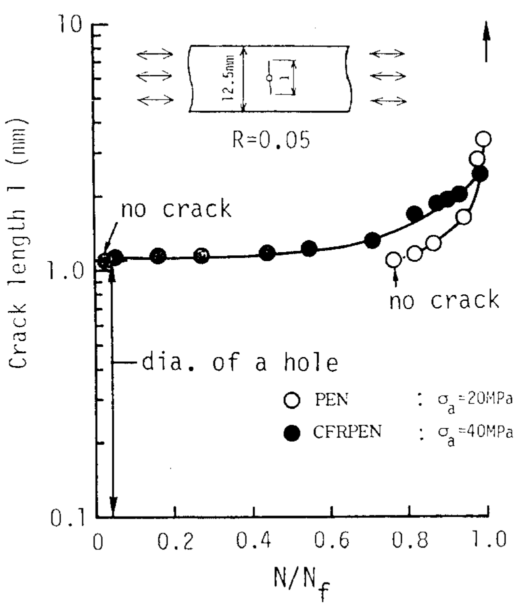


Fig. 9 Fatigue crack propagation curves of PEN and CFRPEN with a small hole of diameter 1.1mm

Fatigue crack propagation curves of PEN and CFRPEN with a small hole of 1.1mm in diameter are shown in Fig. 9. It is clear from this figure that the crack propagation rate PEN fatigue life is very high relatively. In addition, the duration of crack propagation was found to be extremely short in comparison to the total fatigue life. Therefore the fatigue life of PEN is co-

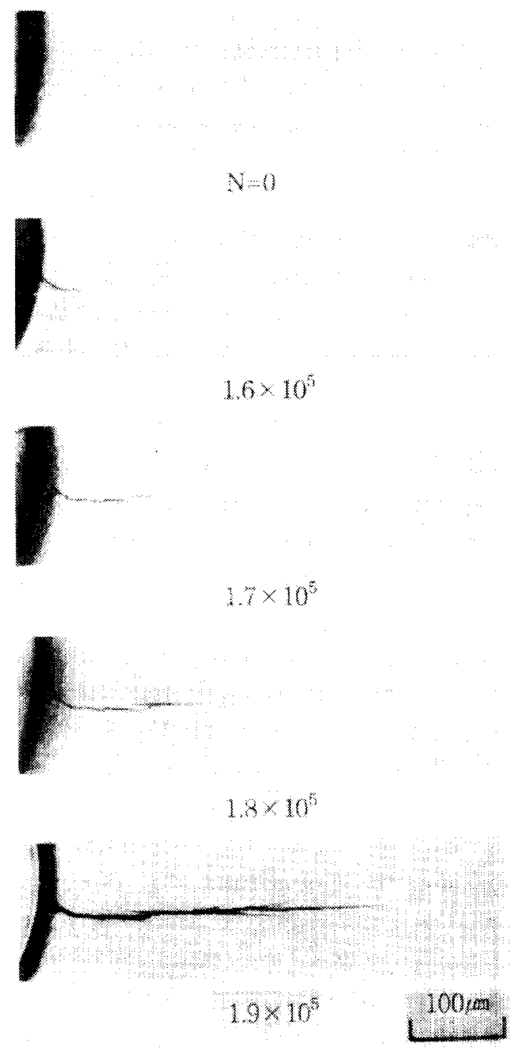


Fig. 10 Change in the surface state of PEN specimen small hole of diameter 1.1mm under fatigue
(σ_a = 20MPa, N_f=1.97 × 10^5 cycles)

ntrolled mainly by the life of crack initiation.

Fig. 10 shows the change in the surface state of PEN specimen with a small hole having a diameter of 1.1mm due to the repetitions of the stress whose fatigue life is 1.97×10^5 cycles. This figure indicates that the fatigue crack initiation of PEN is of the point - initiation type and the fatigue crack propagates in a straight line. This fact supports the author's previous findings regarding the fatigue strength for polyetheretherketone[6].

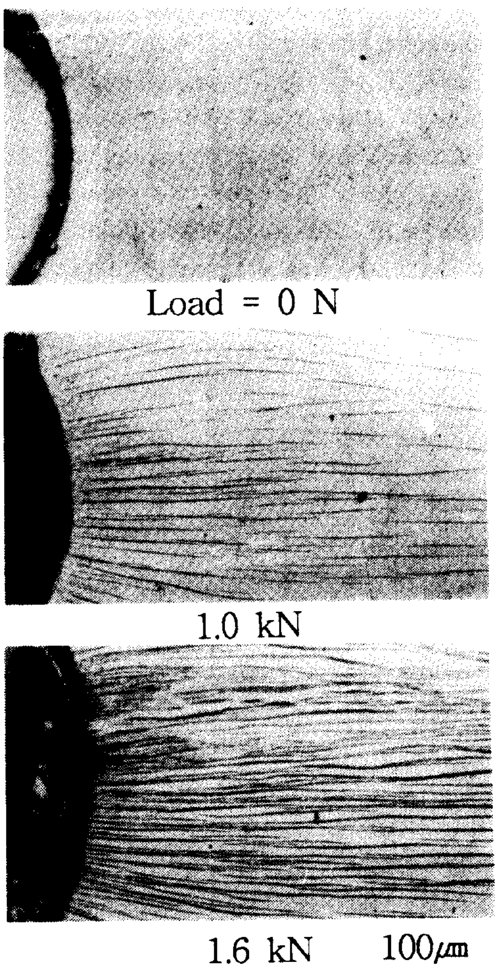


Fig. 11 Change in the surface state of PEN specimen with a small hole of diameter 1.1mm under static tension
(P_f = 1.7KN, Notch depth = 4mm)

In the case of the static tension, on the other hand, at the very early stages of loading, damage in the form of crazes nucleates and grows in the vicinity of the notch prior to crack initiation(as shown in Fig. 11). At first, crazes appear at the notch root. While their density and size increase, new arch shaped crazes form. When the crazes density reaches a critical level, crack nucleates and the specimen fails imm-

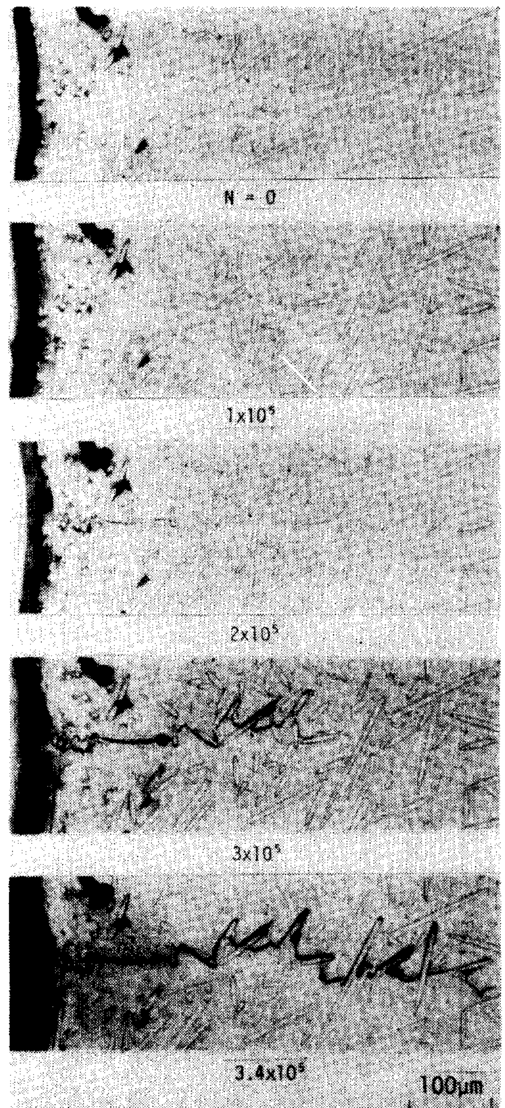


Fig. 12 Crack initiation and propagation process of CFRPEN specimen with a small hole of diameter 1.1mm under fatigue
(σa = 40MPa, $N_f = 3.66 \times 10^5$ cycles)

ediately after crack initiation.

Fig. 12 shows the crack initiation and propagation processes of CFRPEN due to the repetitions of the stress whose fatigue life is 3.66×10^5 cycles. In the case of the CFRPEN, the fatigue crack initiates generally from near the fiber end early as a result of stress concentration, but propagates very slowly owing to the present of fibers. The fibers do not break under this stress level.

During its propagation stage the crack goes around fibers and coalescence with other cracks.

On the contrary to what has been observed in PEN, the crack propagation life of the CFRPEN is extremely long compared with the total life. This means that short carbon - fibers in the CFRPEN specimens give rise to a negative action against fatigue crack initiation and make a positive action against fatigue crack propagation.

4.3 Fatigue Strength of Notched CFRPEN Specimens

Fig. 13 shows the S - N curves of the notched CFRPEN specimens having a diameter of 0.6mm, 1.1mm, 4mm, and 6mm. Based on the examination of the successive surfacereplication, it was found that for the specimens with a notch radius of 0.3 and 0.55mm a non - propagating crack developed only after 10^7cycles(as shown in Fig. 13).

The relation between σ_{w1} and σ_{w2} as a function of the stress concentration factor, K_t, is given in Fig. 14. The limiting stress for macrocrack initiation, σ_{w1}, was defined oringinally as the maximum nominal stress under which a macrocrack does not appear along the notch root, but it is difficult to discriminate the macrocrack initiation in this composite. Thereupon, σ_{w1} is defined in this paper as the assumed limiting stress from Fig. 14 and experimental observation. On the other hand, σ_{w2} is defined as the threshold nominal stress under which the crack developed at 10^7 cycles are the non - propagating crack. The notch root radius at the branch point between σ_{w1} and σ_{w2}, ρ_0, can be assumed to be about 1.5mm. This value is much higher than that of typical annealed carbon steel. On the other hand, it is clear that the fatigue strength of CFRPEN is very sensitive

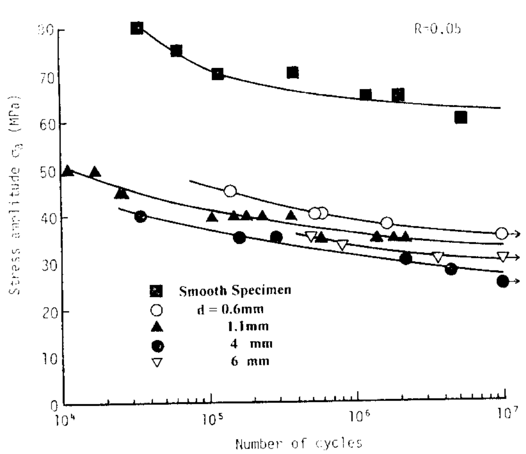


Fig. 13 S - N curves of notched CFRPEN specimens

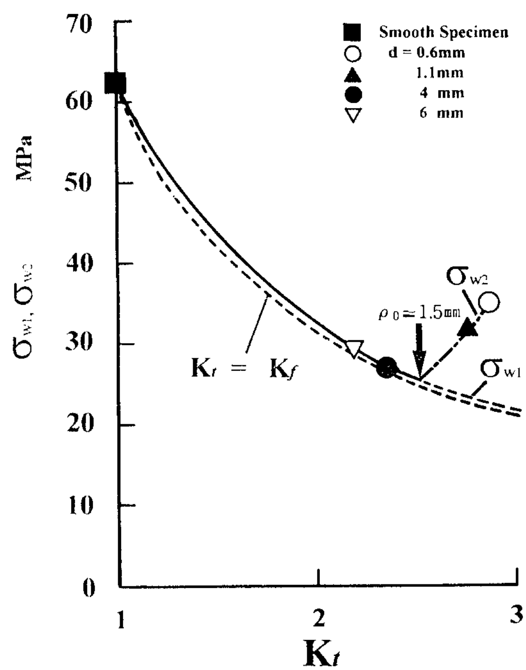


Fig. 14 Relation between dw1 or σ_{w2} and Kt

to a notch because the line of σ_{w1} lies in close proximity to the $K_t = K_f$ line.

The plot of $K_t\sigma_{w1}$ and $K_t\sigma_{w2}$ against $1/\rho$ for CFRPEN based on linear notch mechanics is shown in Fig. 15. Based on the author's previous results, it can be considered that the fatigue strength of an arbitary notched plate specimens of CFRPEN can be estimated from Fig. 15 rearranged based on "linear notch mechanics."

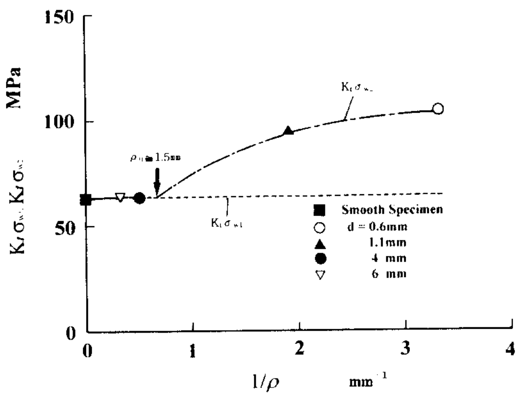


Fig. 15 Relation between $K_t\sigma_{w1}$ or $K_t\sigma_{w2}$ and $1/\rho$

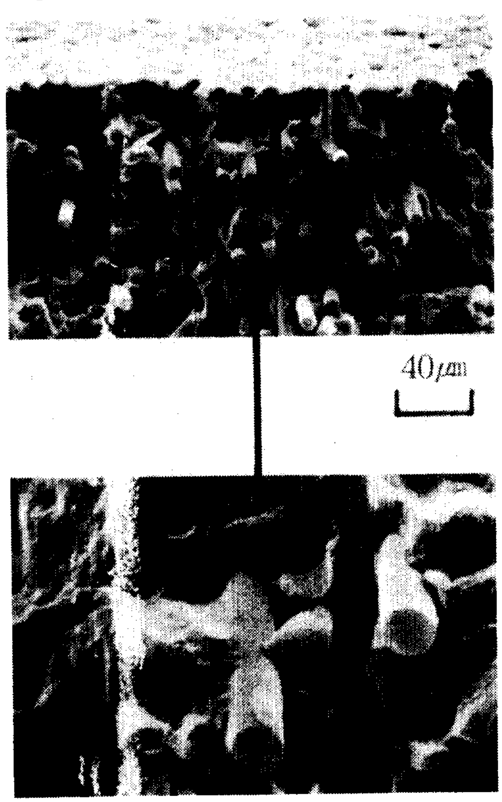


Photo. 2 Fracture appearance

Photo. 2 Shows the fracture appearence of notched CFRPEN specimen(d=1.1mm). The matrix resin in this photograph is elongated and the fibers are covered with matrix resin.

5. Cconclusions

Static and fatigue tests of polyethernitrile (PEN) and CFRPEN specimens in which the short carbon - fibers were combined in the matrix resin with a fiber content of 15% and 30%, by weight, were carried out to investigate the static and fatigue characteristics of plain and notched specimens at room temperature. The fatigue mechanisms in the composite material were clarified through the successive surface observations using the plastic replica method. The results obtained can be summarized as follows.

(1) The occurrence of fracture in PEN and CFRPEN is directly related to σ_{max} and ρ alone independent of the other geometrical conditions.

(2) The relation of $\sigma_c - K_t$ are to be classified into two parts, namely, a part where σ_c decreases with increasing K_t and a part where σ_c is nearly independent of K_t. A similar phenomenon can be seen in notched specimens under fatigue tests.

(3) In the case of the PEN, the fatigue crack initiation is of the point - initiation type and the fatigue crack propagation life is fairly short compared with the total life.

(4) In the case of the CFRPEN, the fatigue crack initiates generally from near the fiber and early as a result of stress concentration at the fiber end, but propagates very slowly owing to the contribution of the fibers.

(5) Short carbon - fibers give rise to a negative action against fatigue crack initiation and does a positive action against fatigue crack propagation in the CFRPEN.

(6) The ratio of the fatigue strength of matrix resin to the one of CFRPEN is a little higher

than that of the tensile strength. And the fatigue strength of CFRPEN is very sensitive to a notch.

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