Fractography of Nylon-6 Yarn

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Synopsis

The breaking mechanism of nylon-6 yarn is investigated, and the breakage of the yarn under simple tensile loading conditions is compared to that of a filament caused by the same loading. The simple model yarn consisting of seven filaments was prepared for this purpose. The yarn was ruptured at a low rate of extension, and the fracture morphologies of the filaments in the yarn were inspected by a scanning electron microscopy. These morphologies are clearly different from those of the filaments broken individually under the same testing conditions used for the yarn. Various kinds of appearances are obtained in the yarn, for example, a large V-shaped notch is observed, the controlled ductile tearing region is developed across the filament at a large angle to its axis, and the ruptured end is expanded into a plane which is perpendicular to its axis. These causes are discussed in detail to understand the breaking mechanism of the yarn.

INTRODUCTION

The tensile breaking behavior of the twisted continuous filament yarns is of importance. There is a difference between the nature of the break in low-twist and high-twist yarns. In low-twist yarns, each filament is virtually independent of the others and breaks when it reaches own breaking extension; namely, the breaking place of the filament and the time required to break the filament, in a constant rate of extension test, are not influenced by the others. When highly twisted, most of the filaments in the yarn break simultaneously, and it can be seen sometimes that these filaments break in a narrow band across the yarn. The breaking mechanism of each filament should be dependent on the transverse forces among filaments. The features of these forces were studied in the previous papers[1,2] and many studies concerning these forces have been done by several authors.[3–6] However, a detailed mechanism of the effect of the transverse forces upon the breakage of the yarn has not yet been discussed on the basis of fractography.

It is well known that the breaking extension of the yarn varies with twist. Although there are several possible explanations of this phenomenon,[7] these seem to involve some uncertainty because the relation among these explanations is not clear. As stated above, the breaking mechanism of the yarn has not yet been explained perfectly. One way to increase understanding of these situations is to observe the fiber fracture morphologies which occur when a yarn is broken.

The study of fiber fracture morphology has been made much easier by the introduction of scanning electron microscopy, which enables the whole fractured surface to be viewed in focus. With the use of this technique, much useful information about fibers has been obtained by Hearle and his co-workers.[8–14] However, since these studies have been concerned with the ruptured surfaces of various single fibers subjected to the different modes of deformation, the problem concerning the yarn has not yet been studied on the basis of fractography.

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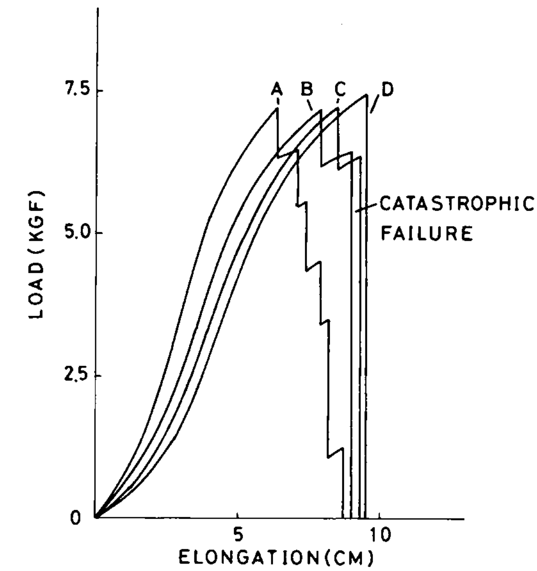


Fig. 1. Typical load-extension curves for nylon-6 model yarns with various geometries. (A) 0 turns/100 mm; (B) 30 turns/100 mm; (C) 35 turns/100 mm; (D) 40 turns/100 mm.

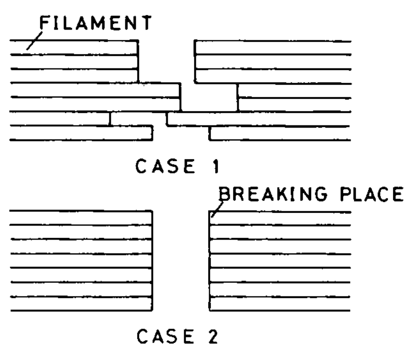


Fig. 2. Schematic diagram of the fractured surface of the yarn.

TABLE I
Specification of Tensile Fracture Conditions of Model Yarn

Sample, (turns/mm)	Number of tensile yarn breaks	Number of occurrences of catastrophic failure	Number of occurrences of Case 1	Number of occurrences of Case 2
30/100	47	41	35	6
35/100	45	45	36	9
40/100	46	44	33	11

The aims of the present work are to make an observation of the fiber fracture surface which occurs when the yarn is subjected to simple tensile loading, and to discuss the breaking mechanism of the yarn.

EXPERIMENTAL

Model yarn consisting of seven filaments was made of nylon-6 coarse monofilament (0.128 mm in diameter) supplied by Toray Industries Inc. The large-diameter filament can be handled easily with tweezer, and various regions in the fracture surface can usually be clearly seen in the coarse monofilament. This hexagonally close-packed yarn is one of the simplest assemblages of the filaments. Furthermore, since this model yarn has a small number of filaments, it is convenient to examine the fracture surface of filaments in the yarn by a scanning electron microscopy. The linear density of this model yarn was 108.4 tex and the length of the yarn was 100 mm. We used flat clamps to measure the load-extension curve so that the yarn was expected to break in the boundary plane. To avoid this phenomenon, both ends of the parallel bundle of the yarn were strengthened by epoxy resin.

One end of the bundle was held in the upper jaw of a Tensilon Tensile Tester, and the other end was held in the lower jaw by using 100 mm gauge length. The pin, which connected the lower jaw with the Tensilon, was removed. An arbitrary twist was inserted in the bundle by rotating the lower jaw. During this operation, contraction of the yarn appeared owing to the twisting, therefore, the lower jaw was moved upward to reduce this effect. Then the pin was reinserted. The change of the gauge length was, of course, taken into account for the estimation of the breaking extension of the yarn. The extension rate of 300 mm/min and the chart speed of 1000 mm/min were used. All the tensile tests were carried out in a controlled atmosphere of 65% relative humidity, 20°C. After tensile testing, one fractured end of the yarn was separated into seven filaments. These filaments were mounted in the fiber clamp which was similar to that used by Hearle and Cross.[9] The filaments and clamp were placed in an evaporating unit and a layer of conductive material (gold) was evaporated onto them, and then the filaments were examined in a scanning electron microscopy. Owing to the fiber clamp used, it cannot be avoided that a little error is introduced into the scale of each photograph.

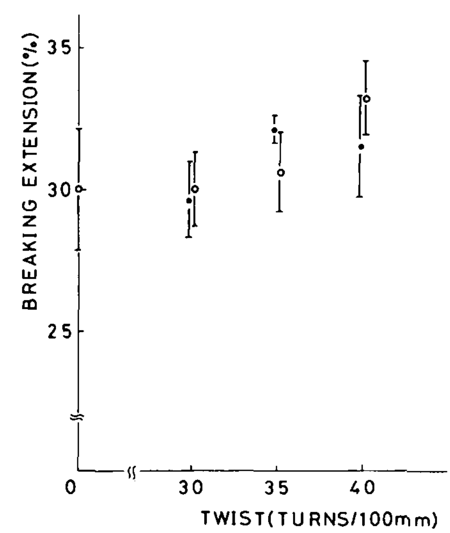


Fig. 3. Variation of breaking extension of the yarn with twist level. (○) Case 1; (●) Case 2.

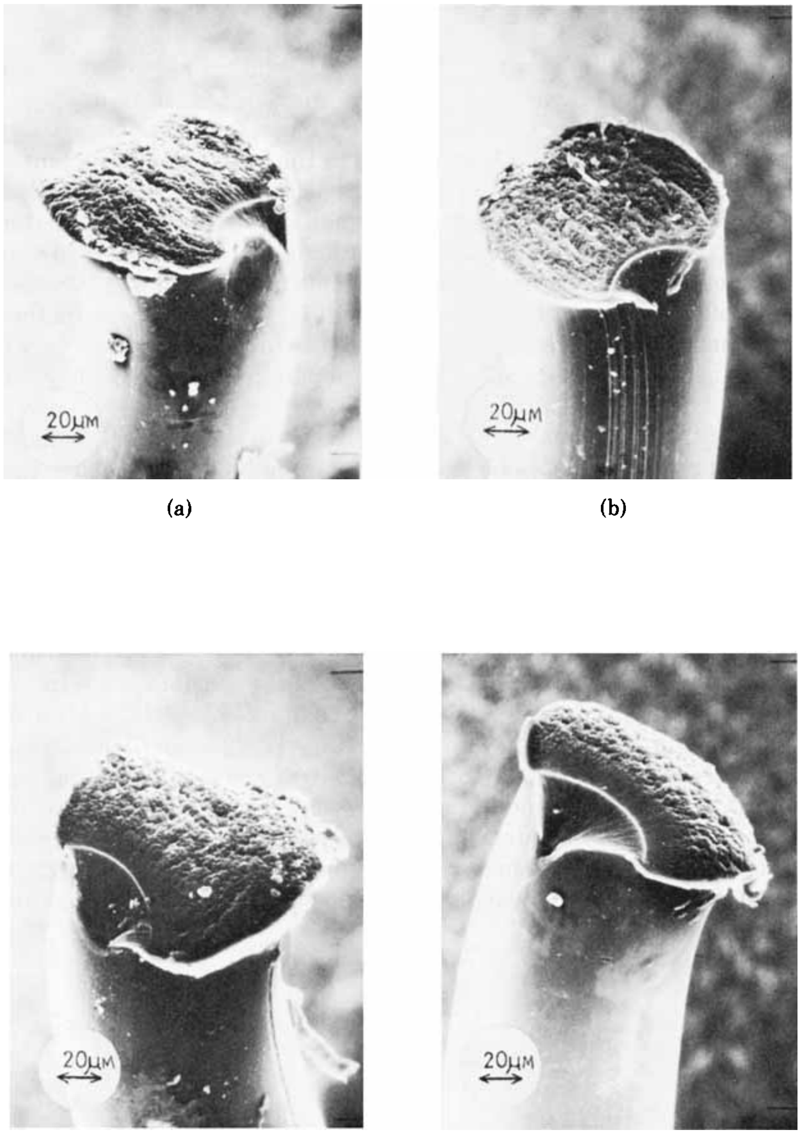
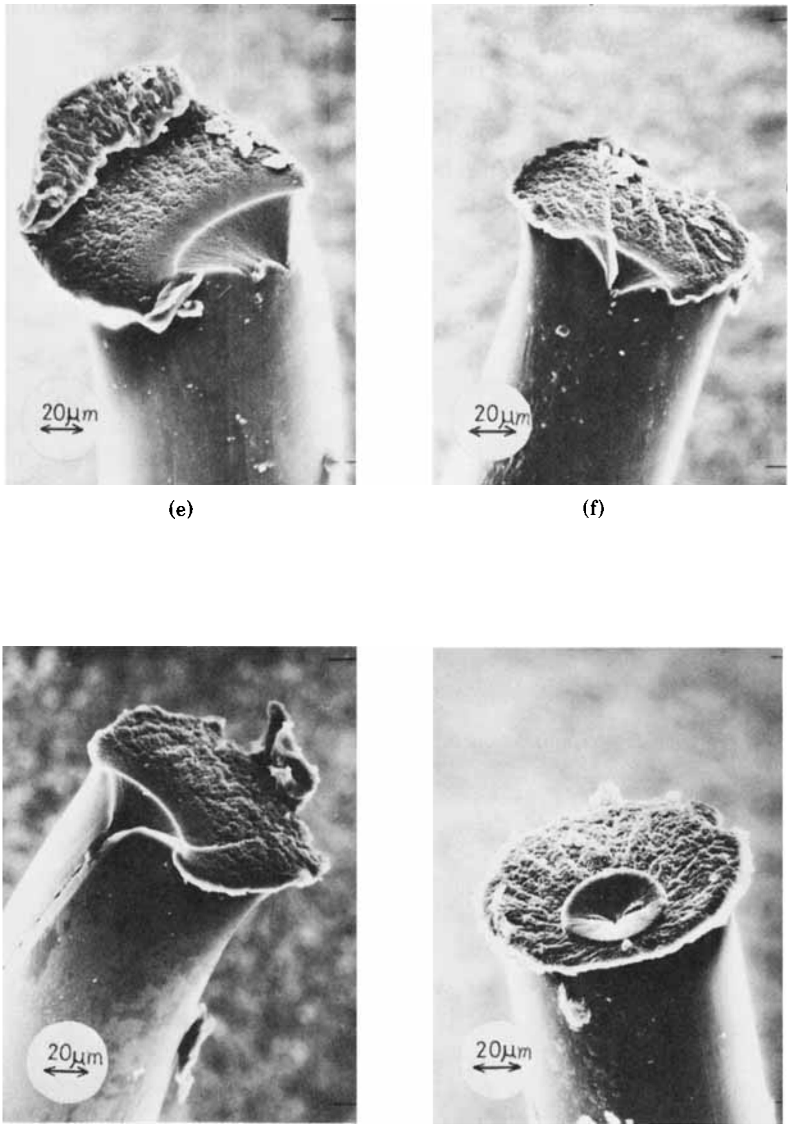


Fig. 4. Tensile fracture morphologies of nylon-6 filament used.

RESULTS AND DISCUSSIONS

Large-Scale Structure Features

A typical set of load-extension curves of the model yarn at various levels of twist is shown (Fig. 1). When the yarn with a high twist is extended, most of the filaments in the yarn break sharply. In this paper, the state is referred to as "catastrophic failure," where the number of filaments breaking separately to whole yarn breaks is smaller than 4. In this state, there are two cases: Case 1, in which the breaking place of each filament is relatively distributed along the yarn direction; and Case 2, in which the breakage of each filament occurs in a



(e) (f)

(g) (h)

Fig. 4. (*Continued from previous page.*)

narrow band across the yarn. These cases are schematically shown (Fig. 2). The experimental data of the load-extension behavior of the yarn are classified into two cases described above, and the result is shown in Table I. The number of occurrences of Case 2 is increased with an increase in twist. Figure 3 shows the variation of breaking extension of the yarn with twist. The breaking extension ϵ_y of the yarn was determined by the position of the catastrophic failure in the load-extension curve and the following equations:

$$\epsilon_y = (L_b - L_c)/L_c, \qquad C_y = L_0/L_c \tag{1}$$

where L_0 is the length of the original parallel strand, L_c is the length of the twisted yarn under zero load, L_b is the length of the twisted yarn extended to break, and C_y is the contraction factor of the yarn.

The breaking extension of the yarn at 0-twist level is determined by the breaking extensions of single filaments. The breaking extension of the yarn, at first, decreases with an increase in twist, and then increases. As seen in Figure 3, there is no regular relationship between the effect of the fracture mechanism

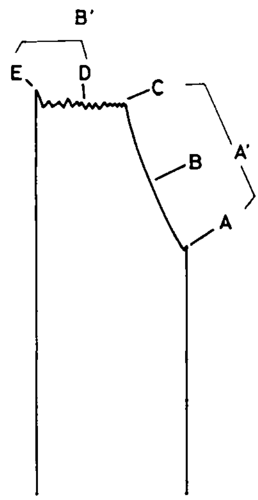


Fig. 5. Diagrammatic representation of fracture surface of a filament.

Fig. 6. Typical morphology of Type I.

Case 1 and the effect of Case 2 upon the breaking extension of the yarn. This means that the breaking extension of the yarn is independent of these cases.

To extend the discussion of the breaking mechanism of the yarn, the fracture surface of the filaments in the yarn should be observed. In the following discussions, the special cases of Case 1 and Case 2 will be investigated, namely, the case where all the filaments in the yarn break sharply in the load-extension curve.

Fracture of a Filament

The same kind of filament used for preparation of the model yarn was ruptured under simple tensile loading. Typical fiber fracture morphologies are shown (Fig. 4). Initiation of fracture and V-notch can be seen in the surface. Some unusual fracture morphologies were also observed. On rare occasions, this type of fracture originates at some gross interior flaw, an example is shown in Figure 4(H). These results are satisfactorily explained by the breaking mechanism proposed by Hearle and Cross.[9] According to them, the fracture mechanism of a coarse filament in tension is classified into five regions, as seen in Figure 5. The notation of each region is used in the following discussions. In this experiment, a clear "slip-stick" phenomenon[8] is scarcely observed in region C at high magnification and a large structural difference between region B and region C cannot be observed. However, there is a clear boundary between both regions distinguished from curved line. In the following discussions, the existence of the B region will be determined by that of the curved line. Finally, the tensile

Fig. 7. Typical morphology of Type II.

fracture morphologies of the filament used in this paper are shown: there is an evidence of V-shaped notch formation, and the dimension of the V-notch is relatively constant.

Breaking Mechanism Case 1

The model yarn with the geometry of 30 turns/100 mm was ruptured in a simple tensile test. Some yarns show the evidence of breaking mechanism Case 1. Although various fiber fracture morphologies are obtained in the yarn whose macroscopic appearance shows the breaking mechanism Case 1, these can be classified into seven types:

Type I

The A' region (see Fig. 5) is developed across the fiber at a large angle to its axis. A typical example is shown (Fig. 6). Since the model yarn used consists of a small number of filaments and a relatively low twist, the filaments in the yarn break mainly due to the axial force along the fiber direction. Therefore, the breakage of the filaments in the yarn is discussed on the basis of the breaking mechanism of a filament caused by simple tensile tension. In the course of fracture of a ductile filament at a low rate of extension, a V-notch is formed by a propagating transverse crack and the relaxation of the fractured part. However, if the crack propagation is extremely higher than the relaxation of material, an undeveloped V-notch, namely, a shallow V-notch is expected to be formed.

Fig. 8. Typical morphology of Type III.

Fig. 9. Typical morphology of Type IV.

Since the shallow V-notch can be seen in Figure 6, the crack propagates across this filament at high speed.

Type II

The controlled ductile tearing *B* region is either obscure or relatively small. A typical example is shown (Fig. 7). From the discussion stated above, it is concluded that this occurrence is also due to extremely high rate of crack propagation.

Type III

There is no evidence of a V-notch formation, and the surface shows a rougher appearance. A typical example is shown (Fig. 8). This morphology is similar to that obtained in extremely high rate of extension test by Goswami and Hearle,[13] although their study was, of course, performed on a single fiber.

As stated above, these types of morphology are clearly related to the high rate of crack propagation. When the yarn is extended, many V-shaped notches may be produced in all the filaments, and then a filament breaks and it returns essentially to its original straight configuration at the same time. Consequently, this breakage may give an impact to the weaker regions, probably V-notches developed to some extent, of surrounding filaments. However, this effect is scarcely seen in these figures; namely, these figures basically imply the following crack propagation mechanism. Once a filament breaks, it gives an impact to

Fig. 10. Typical morphology of Type V.

latently weaker region of the surrounding filaments in a narrow band across the yarn. This impact leads to the initiation of fracture, and a crack propagates through the filament at high speed.

Type IV

A large V-shaped notch is observed. A typical example is shown (Fig. 9). The occurrence of this type may be due to the effect that the unbroken remainder of the yarn behaves as a coherent whole, namely, as a filament with large diameter up to the breakage of the filament. This is easily understood by the application of fracture mechanics[15]: the dimension of a V-notch should be increased with an increase in the diameter of a filament to obtain the given critical value of stress intensity factor.

Type V

The *C* region is well developed. A typical example is shown (Fig. 10). This morphology is probably related to the effect of assemblage of filament and to the high rate of crack propagation.

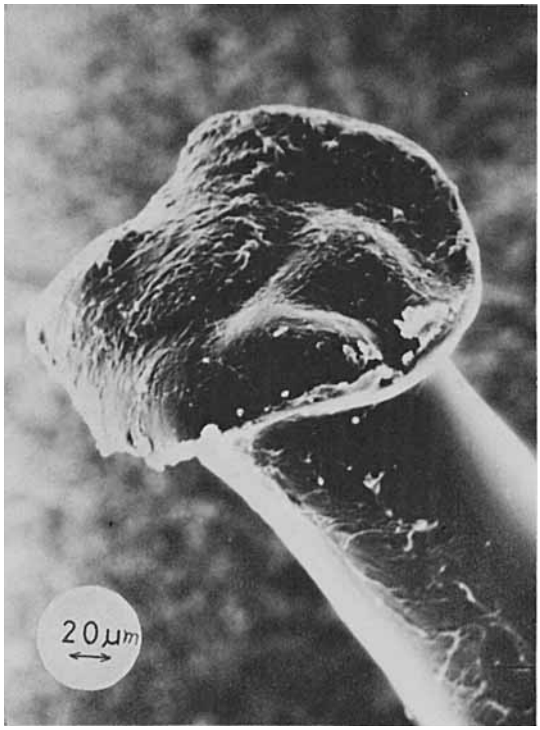
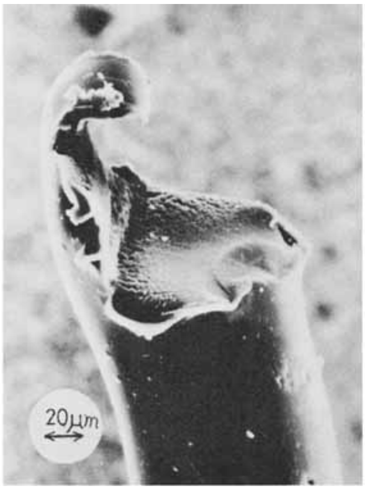


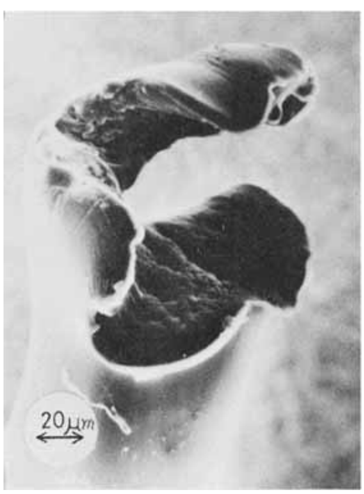
Fig. 11. Typical morphology of Type VI.

Fig. 12. Typical morphology of Type VII.



Type I

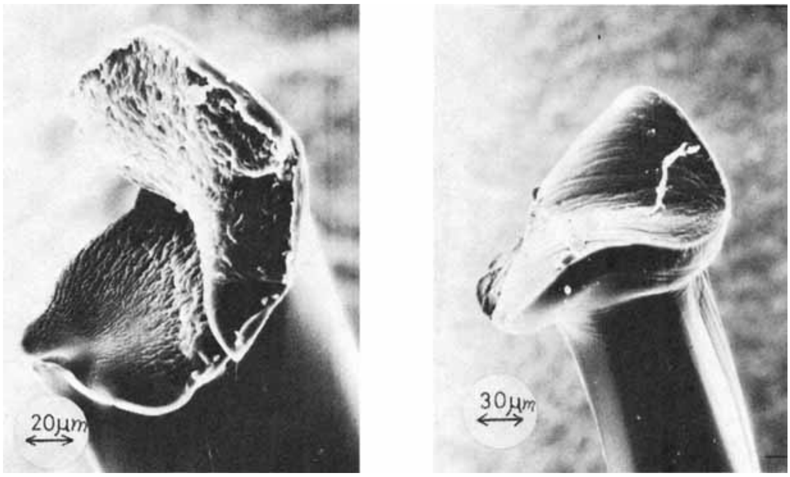
Type II



Type III

Type IV

Fig. 13. Typical fracture morphologies of filaments in the yarn with the geometry of 30 turns/100 mm, whose macroscopic appearance shows the breaking mechanism Case 2.



Type V Type VI

Fig. 13. *(Continued from previous page.)*

Type VI

The fracture surface is expanded into a plane which is perpendicular to fiber axis and indicates the melted appearance. A typical example is shown (Fig. 11). Since this effect is remarkable in Case 2, these causes will be discussed in the section on Breaking Mechanics Case 2.

Type VII

The fiber fractured surface shows not only the morphology of Type VI, but also a damaged lateral surface. A typical example is shown (Fig. 12). This damage is probably due to the interaction among filaments after breaking the filament.

Some broken ends show a complicated morphology, which may be due to the combination of the various types described above. In addition, the similar simple form of a V-notch, seen in Figure 4, is also observed at some cases. Apparently, this filament behaves as a single fiber in the yarn.

Breaking Mechanism Case 2

The model yarn with the geometry of 30 turns/100 mm and that of 40 turns/100 mm were ruptured in tension. Some yarns show the evidence of a sharp break, namely, breaking mechanism Case 2. Although various fracture morphologies of filament are obtained in the yarn whose macroscopic appearance shows the breaking mechanism of Case 2, these can be classified by the same way used in Case 1. Typical results are shown (Figs. 13 and 14). In this experiment, the morphology of Type VII cannot be observed. Furthermore, the morphology of Type II cannot be seen in Figure 14. However, since the other types of morphology related to the high rate of crack propagation can be observed, the mechanism of the crack propagation through the yarn is essentially similar to that in Case 1. In comparison with Case 1, the morphology of Type VI can be

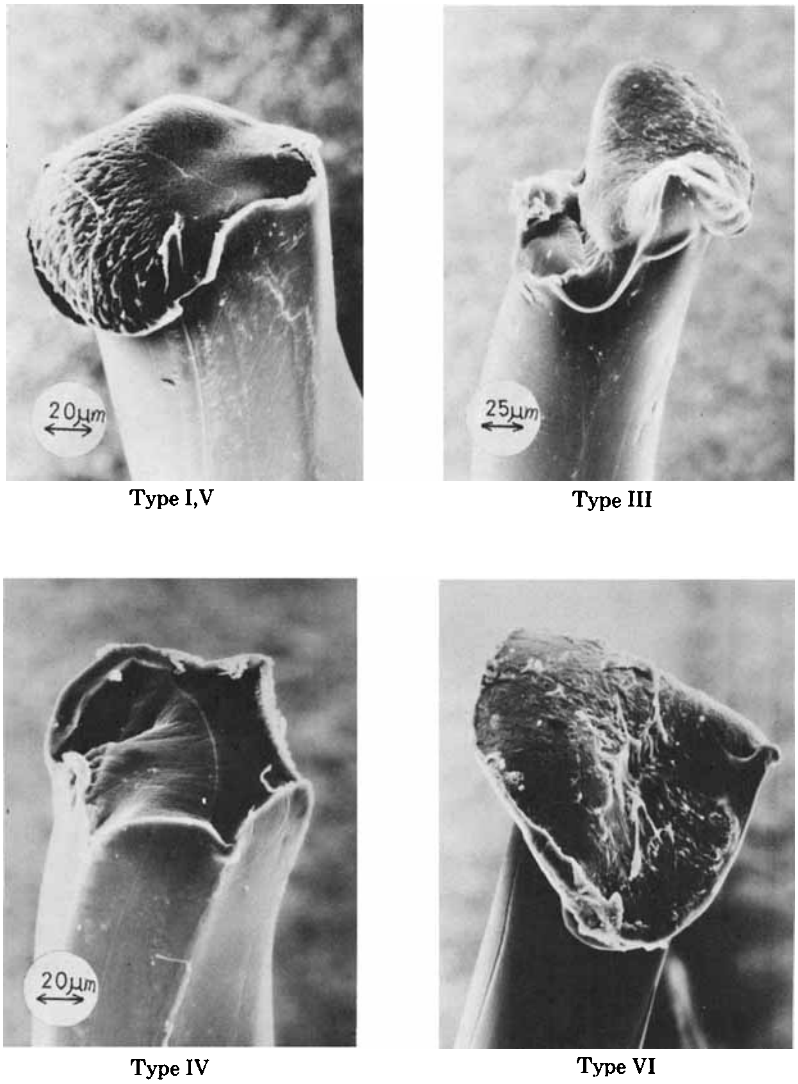


Fig. 14. Typical fracture morphologies of filaments in the yarn with the geometry of 40 turns/100 mm, whose macroscopic appearance shows the breaking mechanism Case 2.

observed in many cases. Let us consider the cause of this occurrence. After the yarn is broken and the transverse forces among filaments are lost at the same time, the broken part, possessing a surplus energy due to high stress concentration in the filament, is isotropically relaxed because of the disappearance of the transverse force, and the surface is melted by the release of the surplus energy during the process. Consequently, the fracture surface is expanded into a plane which is perpendicular to fiber axis, and indicates the melted appearance.

CONCLUSIONS

The fracture surfaces of the filaments in the yarn are observed. These fracture morphologies can be classified into seven types. The causes of these appearances are discussed and the features of the breakages of the filaments in the yarn are

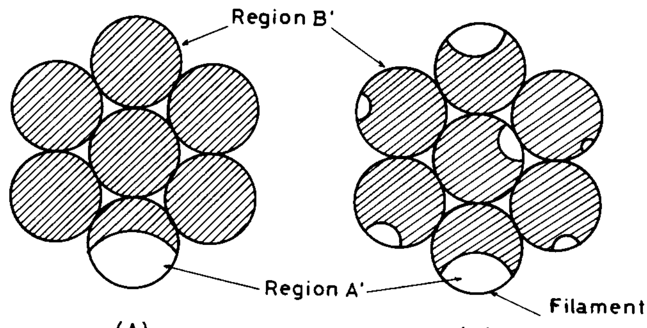


Fig. 15. Schematic diagram of breaking mechanism of the yarn. (A) model expected from macroscopic observation of breakage of the yarn; (B) model expected from observation of fractured surface of filaments.

understood. Furthermore, from another point of view, let us discuss the cause of appearances of the fiber fracture morphologies related to high rate of crack propagation. From the macroscopic observation of the breaking mechanism of Case 2, it is expected that the twisted yarn behaves as a coherent whole, namely, as a filament with large diameter during the breakage under simple tensile loading conditions. In this case, the following effects are expected: a large V-notch is observed in the filament and only the region B' (see Fig. 5), which is extended in overall area of cross section of the filament, can be seen in the other filaments. This expected breaking mechanism is schematically shown in Figure 15(A). However, this expectation is not realized, as seen in Figures 13 and 14; namely, the initiation of fracture can be seen in most filaments in the yarn. From this observation, the mechanism of crack propagation among filaments is considered as follows: one filament breaks and it returns essentially to its original straight configuration at the same time. This gives an impact to the weaker region of the surrounding filaments in the narrow band across the yarn. The initiation occurs in the filament, and the crack propagates across the filaments at extremely high speed. Then the whole yarn fails by the repeated fracture of individual filaments. This is the mechanism of crack propagation among filaments in the model yarn. This crack propagation mechanism is schematically shown in Figure 15(B). Similar propagation mechanism may be essentially operated in an actual yarn consisting of a small number of fine filaments.

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