Composites with High Work of Fracture [and Discussion]

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Composites with high work of fracture

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[Plates 1 and 2]

Results obtained when investigating the fracture behaviour of wood have suggested the possibility of making composite materials with high work of fracture and low density, at the expense of moderate loss of stiffness.

The reinforcing elements of the composite are made in the form of cylindrical tubes with helically wound walls of glass or carbon fibres, simulating, to a certain extent, the structure of wood cells.

The hollow tubes, under tensile stress and in certain circumstances, are capable of deforming pseudo-plastically absorbing large amounts of energy in a manner which is effectively similar to that of ductile fibres

Work of fracture in excess of 4×10^5 J/m^2 has been obtained, comparable to that of ductile metals. The dependence of the work of fracture on various parameters will be discussed together with some suggestions for compensating for the loss of stiffness without reducing the energy absorbing capacity of the system.

1. Introduction

When composite materials are used for exacting engineering purposes there is generally a need not only for high strength and stiffness, but also for toughness. However, in designing advanced composites we are liable to encounter a difficulty which is inherent in the development of all structural materials and which is implicit in fracture mechanics. This is the difficulty that, when the working stresses in a material are increased or when its Young modulus is improved, it is not sufficient merely to maintain a constant value for the work of fracture. If, under the more advanced conditions, we are to preserve the same standard of safety as before, that is to say the same critical crack length, then the work of fracture must be increased as the square of the applied stress. It is true that, from the Griffith equation (Griffith 1920), the work of fracture can apparently be reduced as the stiffness of the material is increased but, in practice, this is not really the case. This is because the stiffer a material is made, the less its resilience or strain energy storage will be at any given stress. Thus such a material is the more likely to break under dynamic conditions. Therefore, in the new high modulus fibre materials the work of fracture needs to be very large: most probably considerably higher than can be achieved using the accepted present-day methods of manufacture. The failure of the Rolls-Royce carbon fibre fan blades a few years ago lends weight to this view.

Unfortunately with composites – as with most materials – it is difficult to combine high work of fracture with the best strength and stiffness since these requirements are, to a large extent, conflicting. This is why the properties and morphology of timber are of especial interest, not only for their own sake, but also because we have found that the work of fracture mechanism that has been evolved by trees is applicable to the design of artificial composites. Timber is, after all, not only an efficient structural material but also an exceptionally safe one, and it is sometimes forgotten by modern materials engineers that aeroplanes have been made from wood for many years, and with considerable success.

Weight for weight, the strength and stiffness of timber along the grain compares well with the best engineering metals and so does its work of fracture across the grain. We think that the high values for the work of fracture of wood cannot fully be accounted for by calculations based on contemporary composite theory, supposing the wood to be made from fibres arranged in any of the ways that are usual in reinforced plastics. We have therefore been led to look for a novel energy-absorbing mechanism incorporated, by some means, in the fine-scale structure of the timber.

In the present communication we have restricted ourselves to a short account of how such a mechanism was found to exist in wood and of how a similar principle was applied to the making of artificial fibrous composites where its use resulted in a large increase in toughness. It is hoped to give much fuller details of both the theory and the experiments on which this research has been based in two subsequent papers, which are in preparation.

2. The magnitude of the fracture energy of wood

During the course of our research the work of fracture of several species of wood was measured, with different techniques and under varying conditions of temperature and moisture (Gordon & Jeronimidis 1974; Jeronimidis 1976). On the whole, the results were very consistent and are in substantial agreement with the values reported by other workers (Tattersall & Tappin 1966; Schniewind & Centeno 1973; Chapell & Morley 1976). Typically, for medium density timbers from spruce (*Picea sitchensis*), s.g. 0.38, to teak (*Tectona grandis*), s.g. 0.55, the work of fracture lies in the range 0.9 to 1.6×10^4 J/m^2. Low density woods, such as balsa (*Ochroma* sp.) have lower absolute works of fracture but, in general, their specific works of fracture are fairly constant. Furthermore, these values are not greatly affected by changes in temperature or in moisture content.

The specific value of the work of fracture of most timbers is thus generally in the region of 3×10^4 J/m^2. It is not without interest to compare this value with those for engineering metals such as steels. The specific gravity of iron and steel is about 7.8 and so the corresponding absolute value for the work of fracture of a material as dense as steel would be about 2×10^5 J/m^2. A steel with such a work of fracture would have a tensile strength of perhaps 400 MPa (6×10^4 lbf/in^2). However, the tensile strength of spruce, for instance, is about 100 MPa or 14×10^4 (lbf/in^2). So, for the same specific work of fracture, spruce has five times the specific tensile strength of steel. Since the specific Young modulus of spruce is also slightly higher than that of steel, wood may be said to possess a very remarkable combination of properties. Even if the comparison be made on the basis of bending, rather than tensile strength, the result is still very favourable to wood, since the 'modulus of rupture' of spruce is about 60 MPa (8×10^3 lbf/in^2).

3. The energy absorption mechanism in timber

Although energy absorption during fracture in artificial fibrous composites is a rather complex process it is generally considered that the bulk of the work is accounted for by the frictional losses which occur during fibre pull-out. Kelly (1973) has predicted this quantity algebraically, and his equation suggests an upper limit for the specific work of fracture of conventional parallel fibre composites which is barely equal to the experimental values for wood. In fact, when one looks at the gross fracture morphology of timber, it seems more reasonable to take a value for the pull-out energy of wood of something like an order of magnitude lower than that fracture energies actually observed. In other words it seems unlikely that the major part of the work of fracture of wood was accounted for by simple fibre pull-out of the Kelly type.

The clue to the solution of this problem was suggested by a publication by Page *et al.* (1971). In this paper Page showed that when single wood cells were tested in tension, some of them showed a pseudo-plastic behaviour which curiously resembled that of a ductile metal – even to the existence of a distinct yield point on the load–extension curve. Furthermore, although cellulose fibrillae themselves seldom show breaking strains of more than 2 or 3%, some of the cells studied by Page exhibited elongations as high as 20%.

The morphological feature of wood which causes this behaviour is the character of the secondary (or S_2) layer of the cell wall. This is, in fact, the principal load-bearing component in the wood. The cell wall is, of course, a hollow tube, often of rectangular section. The important S_2 layer is made up of helically disposed cellulose fibrillae which, considered individually, have an elastic or Hookean behaviour. These fibrillae are wrapped around the cell at an angle which varies between about 10° and 40° (Cowdrey & Preston 1966). A further important fact is that the cellulose fibrillae are always wound round the cell asymmetrically and that, in any one tree, all the cells are wound in the same sense.

Now a tension structure consisting of a hollow tube helically wound with elastic fibres is elastically unstable (Pagano *et al.* 1968) and, when pulled, can undergo what is called 'tension buckling.' When this happens there will be a considerable – and fairly sudden – tensile elongation. The apparent 'yield point' in a wood fibre thus corresponds to the sudden buckling of the tube or cell wall under tension. After buckling, such a tube will not, as a rule, regain its original form and so may show a very large irrecoverable absorption of energy.

Although not all the fibres in a given cross section of wood actually buckle in this manner when wood fractures, a considerable number of them, perhaps about 10%, do so. Such behaviour has repeatedly been observed at the fracture surfaces of timber by means of the scanning electron microscope (figure 4, plate 1). The energy absorption per unit volume of material which occurs when a fibre buckles in this way can be shown to be very large and is, in fact, at least an order of magnitude greater than that needed to account for the measured work of fracture of timber.

4. MODEL EXPERIMENTS WITH INDIVIDUAL HELICALLY WOUND TUBES

Hollow cylindrical tubes with helically wound fibre walls have been made by using a special winding machine which enables the fibre winding angle to be varied. After impregnation with a suitable resin and subsequent curing, such tubes or elements simulate the secondary wall of a wood cell. When loaded in tension and prevented from rotating, these tubes buckled and showed an elastic–plastic behaviour very much like that of a wood cell. A typical load–extension curve for a winding angle, $\theta = 15°$, is shown in figure 1.

Figure 5 (plate 2) shows the onset of tension-buckling instability. The buckling or distortion progresses down the whole length of the tube before complete fracture occurs.

The axial modulus and the buckling stress for a range of winding angles have been calculated from composite theory and are in good agreement with the experimental results. The energy absorbed irreversibly by tubes with different helical angles has been obtained by measuring the areas of the tensile stress–strain curves and also from three-point bending fracture tests on brittle resin beams reinforced with single tubes or macrofibres. The means of two measurements of energy absorption for each winding angle for tubes of about 1.5 mm diameter and 80 mm gauge length are given in table 1.

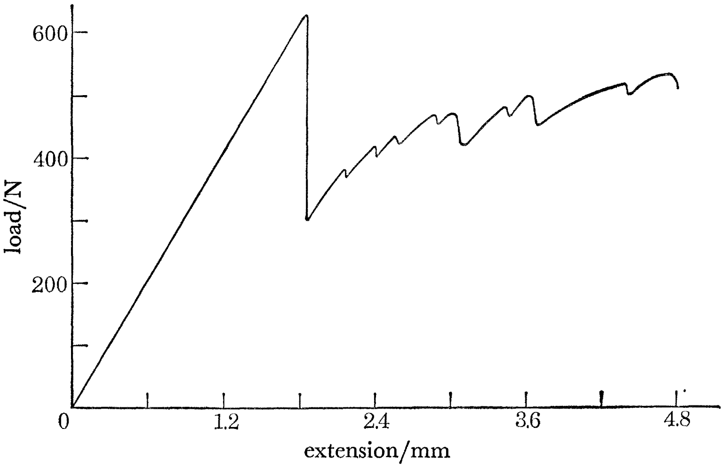

FIGURE 1. Load–extension curve for a macrofibre with $\theta = 15°$. The maximum corresponds to the onset of buckling.

TABLE 1. ENERGY ABSORPTION CAPACITY OF MACROFIBRES

winding angle, θ/deg.	10	15	25	35
energy absorption per macrofibre, w/J	0.9	2.2	1.5	1.1
approximate equivalent energy absorption per cubic metre/10^6 J	6.8	16.7	11.4	8.3

The work of fracture obtainable for a composite made from such cells will be given by multiplying the energy absorbed per unit volume at the given winding angle (second row of table 1) by the disturbed length. In the composite we have made, this length is around 30 mm.

5. COMPOSITES REINFORCED WITH HELICALLY WOUND ELEMENTS (MACROFIBRES)

From the results obtained with single macrofibres, one would expect that a composite reinforced with such elements will have a high fracture energy, provided that in the constrained situation the pseudo-buckling behaviour remains effective. The work of fracture of the composites has been measured by three different methods. Details of testing will be published elsewhere. The mean value of the work of fracture obtained from quasi-static three-point bending tests of notched bars and from tensile tests of single-edge notched specimens have been plotted in figure 2 as a function of the winding angle, θ, of the macrofibres. There is a maximum in the region of $\theta = 15°$, which is consistent with the results in table 1.

It must be pointed out that the graph of figure 2 represents a general trend. Absolute comparisons between different testing methods are difficult and a further complication is introduced by the fact that, for the different winding angles, the various composites have a different volume fraction of glass fibres.

Figures 6, 7 and 8 (plate 2) show the fracture surfaces for three different values of θ. It can be seen how the fracture morphology varies with θ and how the failures within the macrofibres follow the fibre angle. Figure 9 (plate 1) shows a tensile failure for a single-edge notched specimen, illustrating the pseudo-buckling of the reinforcing elements.

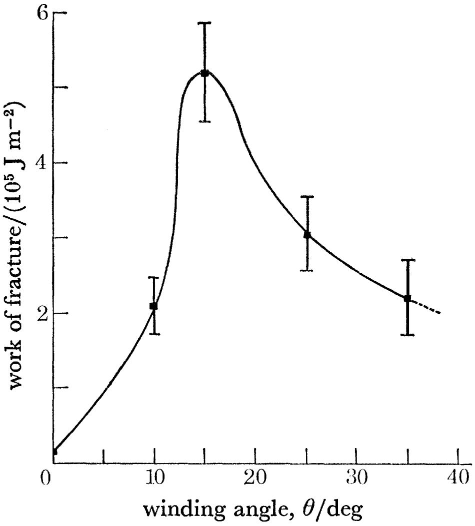

FIGURE 2. Variation of work of fracture with winding angle θ for composites reinforced with hollow cylindrical macrofibres.

In order to assess the relative merit of the different winding angles in providing a suitable combination of stiffness and strength on the one hand and work of fracture on the other, the following two quantities have been used:

$$a(\theta) = \frac{E(\theta)\,w(\theta)}{E(\theta = 10)\,w(\theta = 10)}, \quad b(\theta) = \frac{\sigma_b(\theta)\,w(\theta)}{\sigma_b(\theta = 10)\,w(\theta = 10)},$$

where $E(\theta)$ is the axial modulus of the macrofibres, $w(\theta)$ their energy absorbing capacity (see table 1) and $\sigma_b(\theta)$ their buckling strength.

These two ratios have been plotted as a function of θ in figure 3. It can be seen that, based on this comparison, the best compromise between loss of stiffness and strength due to θ and increase in work of fracture is obtained for $\theta \approx 15°$.

6. CONCLUSIONS

The work that has been described shows that it is possible to produce composite materials with work of fracture comparable to those of ductile metals provided that one is prepared to sacrifice some of the stiffness and strength obtainable from a fully aligned conventional composite. However, for many practical applications, where the loads are applied in bending or in compression $E^{\frac{1}{2}}/\rho$ and $E^{\frac{1}{3}}/\rho$ will be more important criteria than simple specific strength or stiffness (i.e. E/ρ or $\sigma_{\max}/\rho$). Thus, when the reduction in density due to the presence of holes is taken into account, a structure made from such material may still turn out to be lighter than one made from a conventional solid composite.

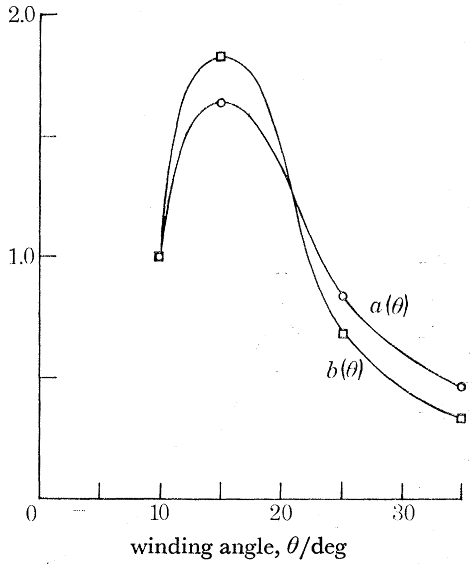

FIGURE 3. Relative efficiency of macrofibres for stiffness, strength and work of fracture.

Furthermore, it has been found that it is possible to compensate to a certain extent for the loss in stiffness and strength. The composites that have been made have still a large proportion of resin due to the gaps left from the packing of the macrofibres. It is possible to fill these gaps with parallel strands of glass fibres or carbon fibres and thus increase stiffness and strength.

The results obtained with glass fibres are very promising. The stiffness can be increased without any significant loss of work of fracture with respect to the standard composites. Figure 10 (plate 1) shows the tensile failure of such a 'hybrid' system (macrofibres with $\theta = 15°$ plus straight glass fibre strands). The major characteristics that give the high work of fracture are preserved.

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Discussion

M. O. W. RICHARDSON (*Department of Materials Technology, Loughborough University, Leicestershire, U.K.*). On the matter of reinforcement by helical fibre springs I should like to point out that the essential 'springiness' and shape of these systems could be enhanced, and their tendency to unwind reduced by turning the spring inside out. The same principle is used during the manufacture of telephone headset cables when the wire is wrapped round a mandrel, heat set, and then after cooling turned inside out. This simple observation may be of some practical use to Dr Jeronimidis.

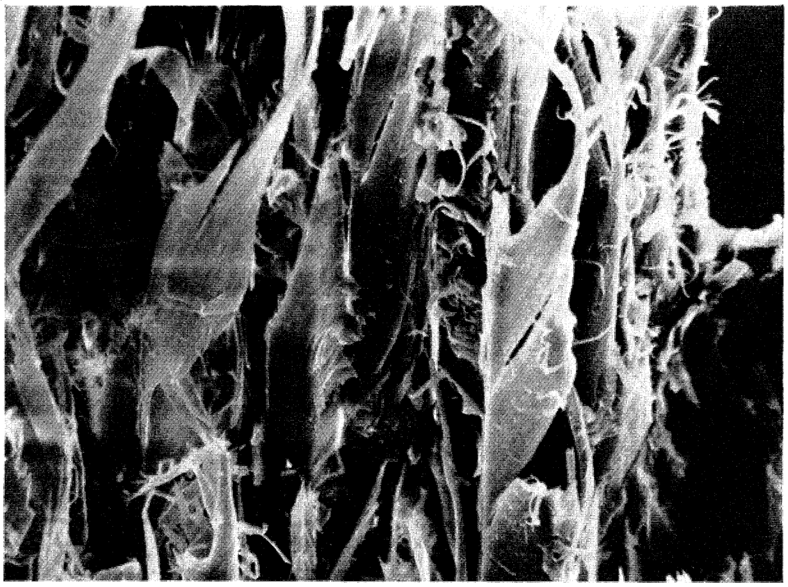


FIGURE 4. Tensile failure across the grain in Sitka spruce (magn. × 680).

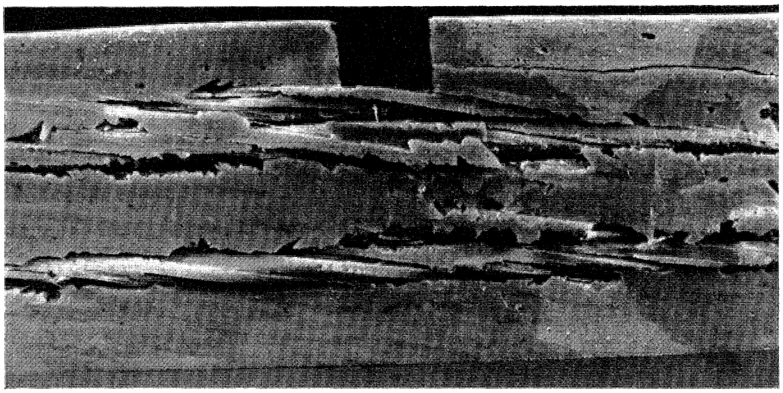


FIGURE 9. Tensile failure of single-edge notched composite reinforced with macrofibres of winding angle 15° (magn. × 6).

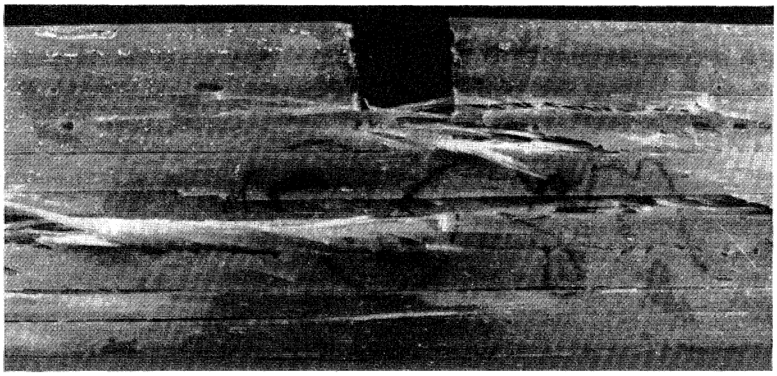
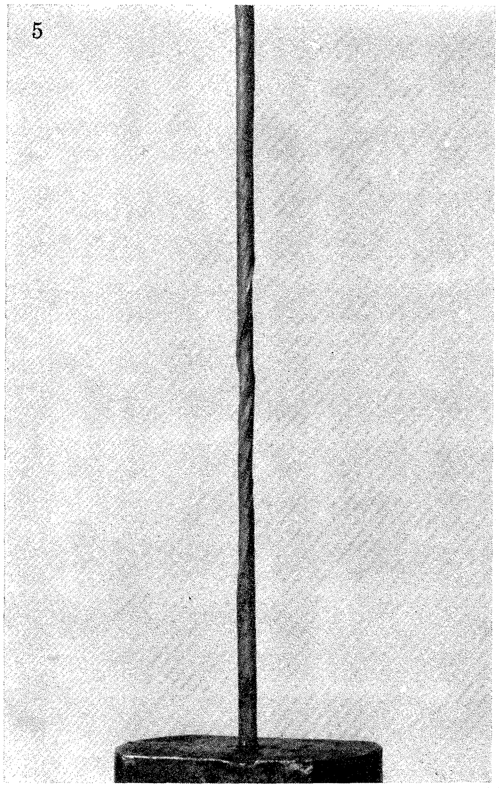


FIGURE 10. Tensile failure of single-edge notched composite 'hybrid' (magn. × 6).



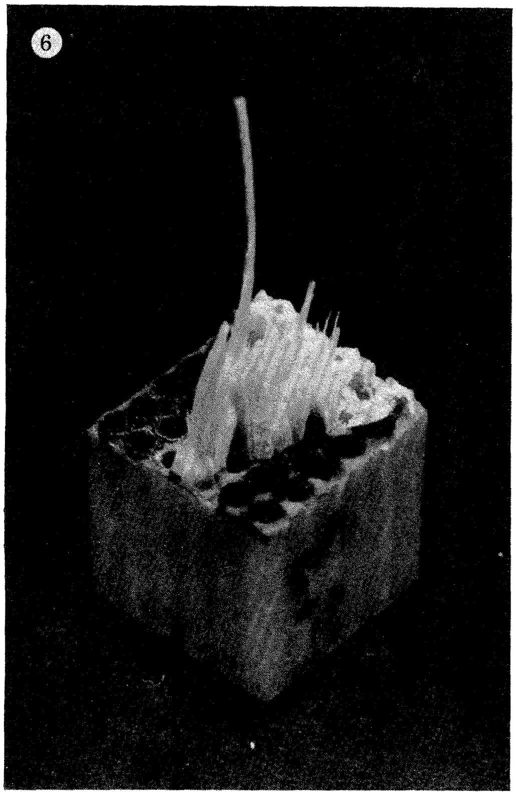


FIGURE 5. The onset of buckling in tension for a macrofibre with $\theta = 15°$ (magn. × 3).

FIGURE 6. Fracture morphology for composite reinforced with macrofibres of winding angle 15°. Bending fracture (magn. × 4).

FIGURE 7. Fracture morphology for composite reinforced with macrofibres of winding angle 25°. Bending fracture (magn. × 4).

FIGURE 8. Fracture morphology for composite reinforced with macrofibres of winding angle 35°. Bending fracture (magn. × 4).

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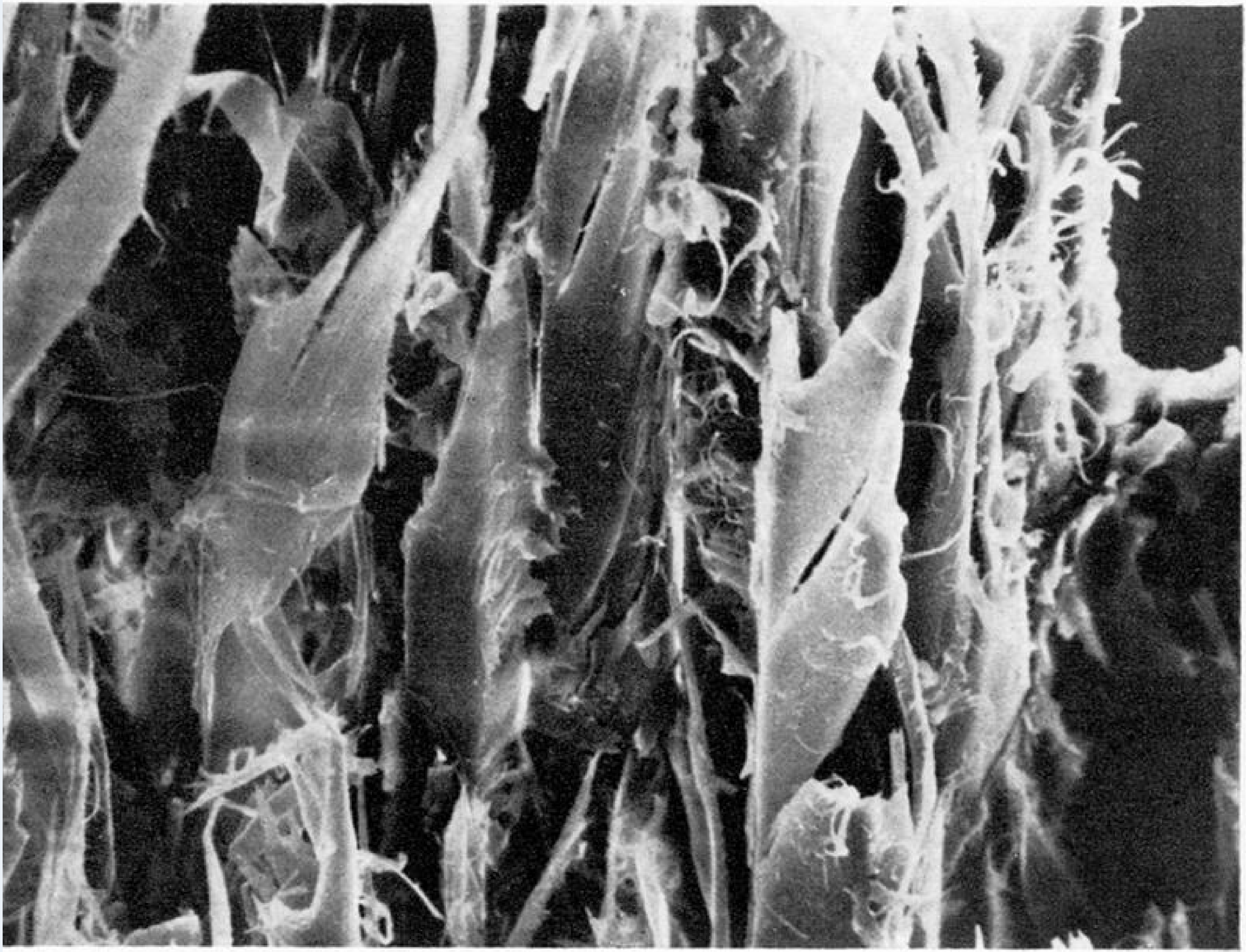
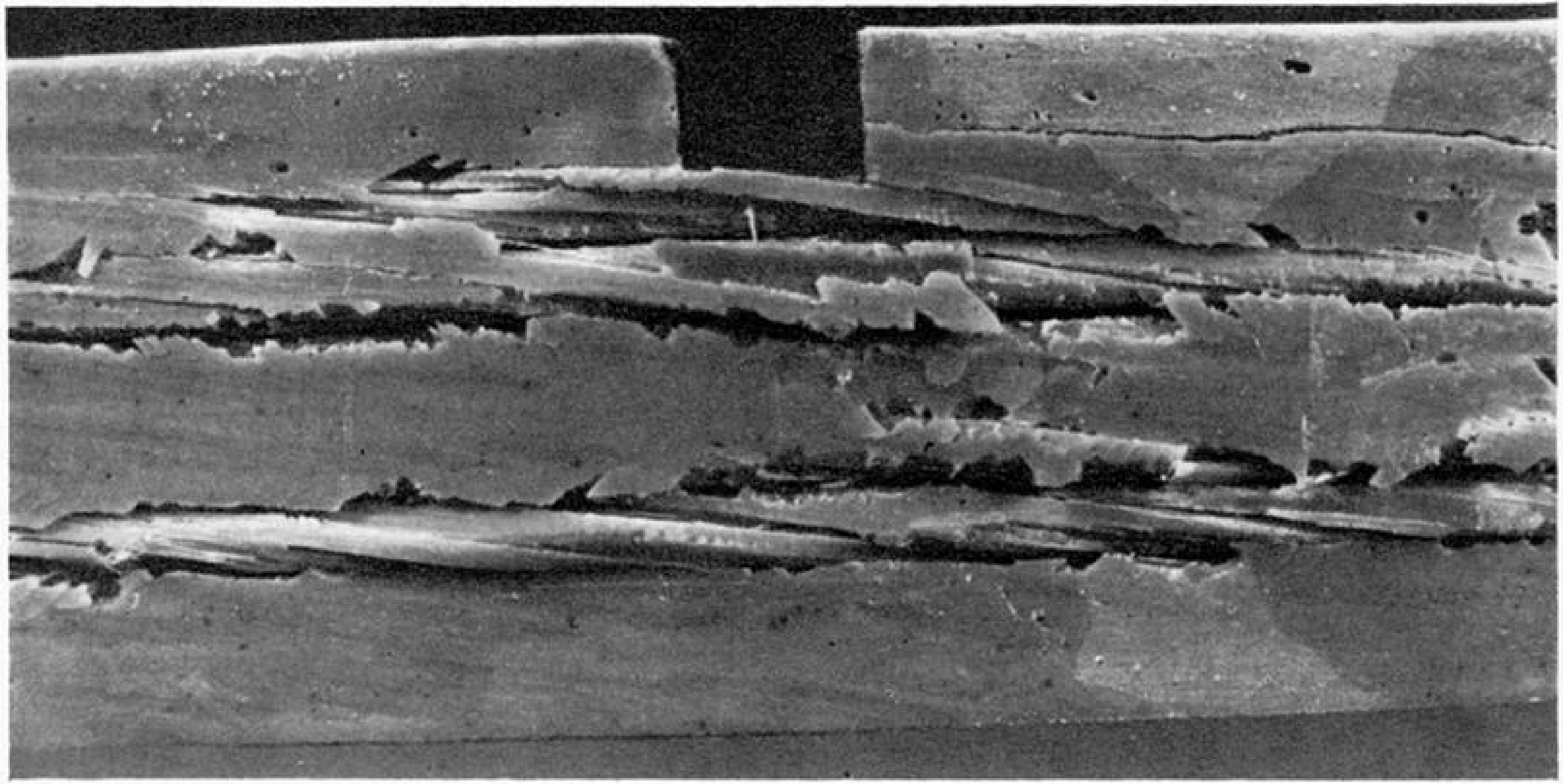


FIGURE 4. Tensile failure across the grain in Sitka spruce (magn. × 680).



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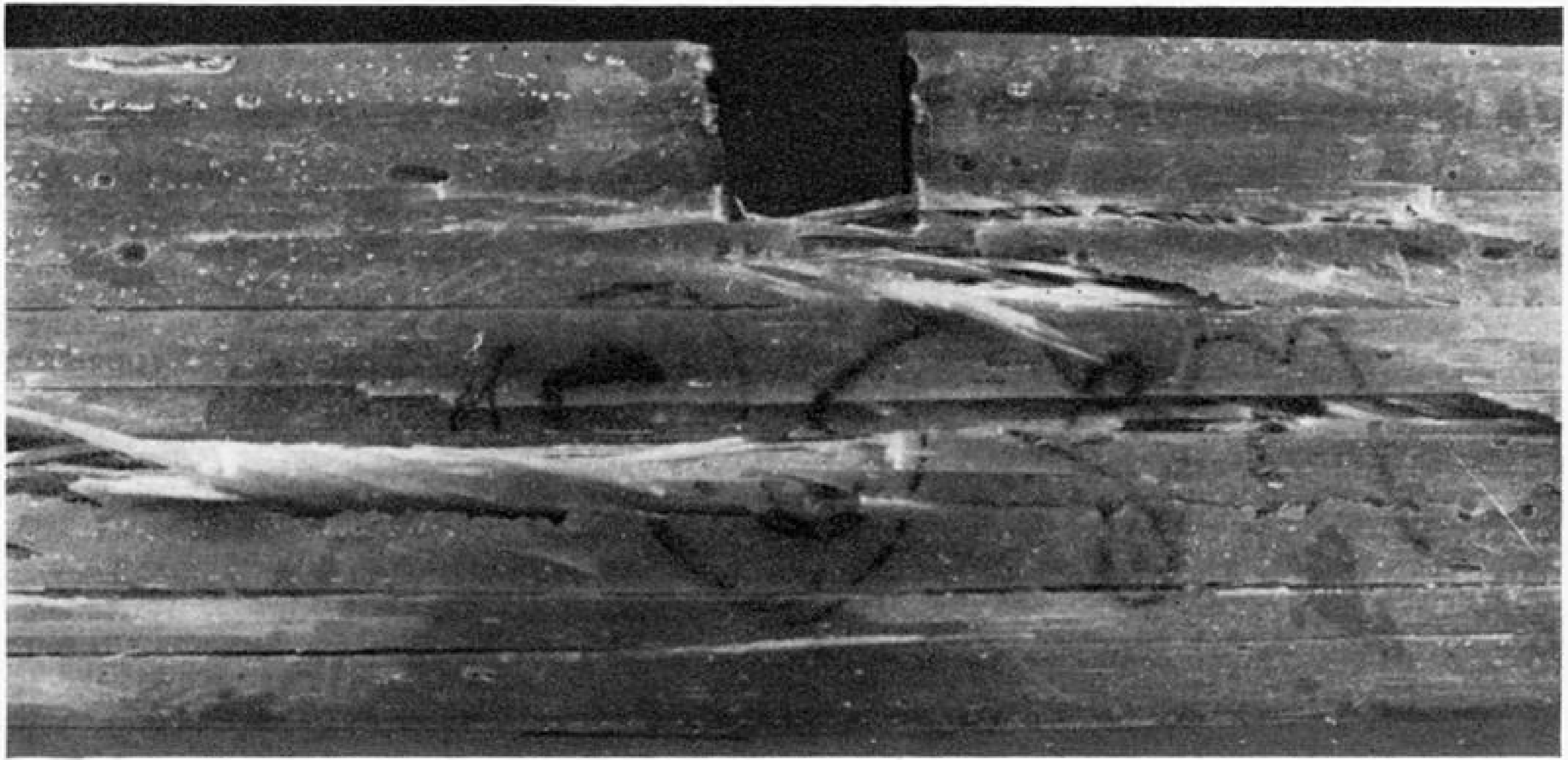
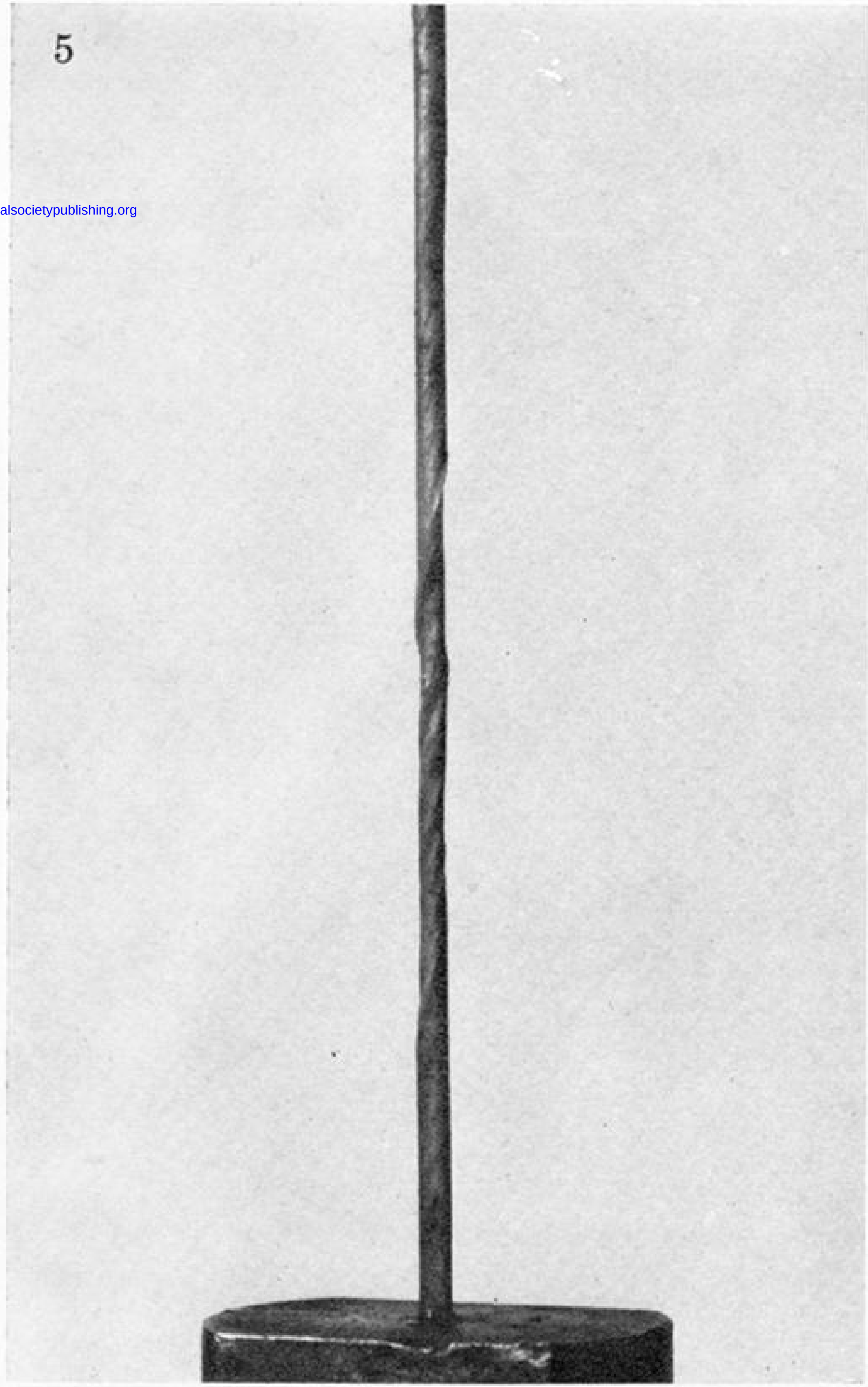


GURE 10. Tensile failure of single-edge notched composite ‘hybrid’ (magn. × 6).



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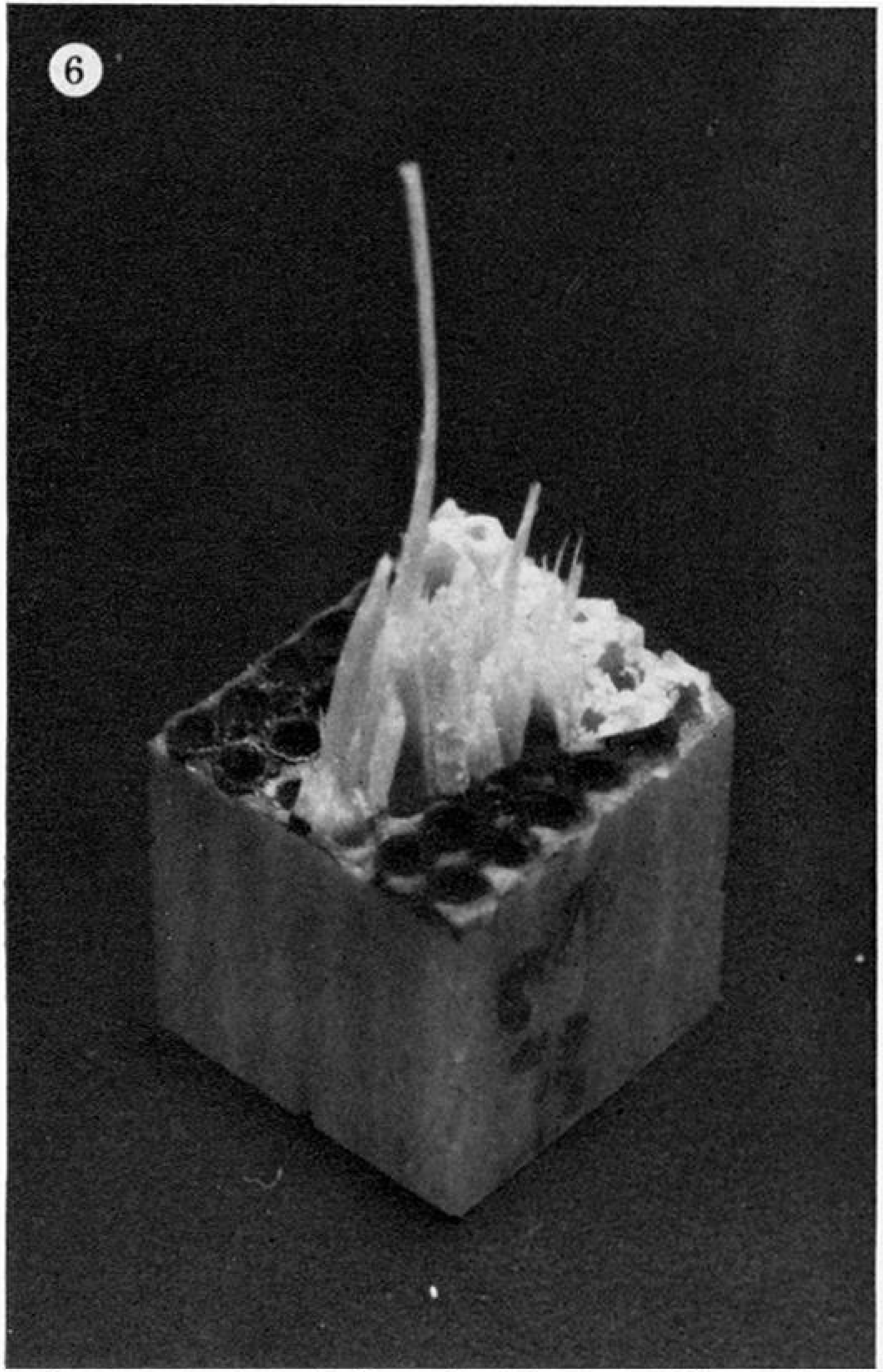
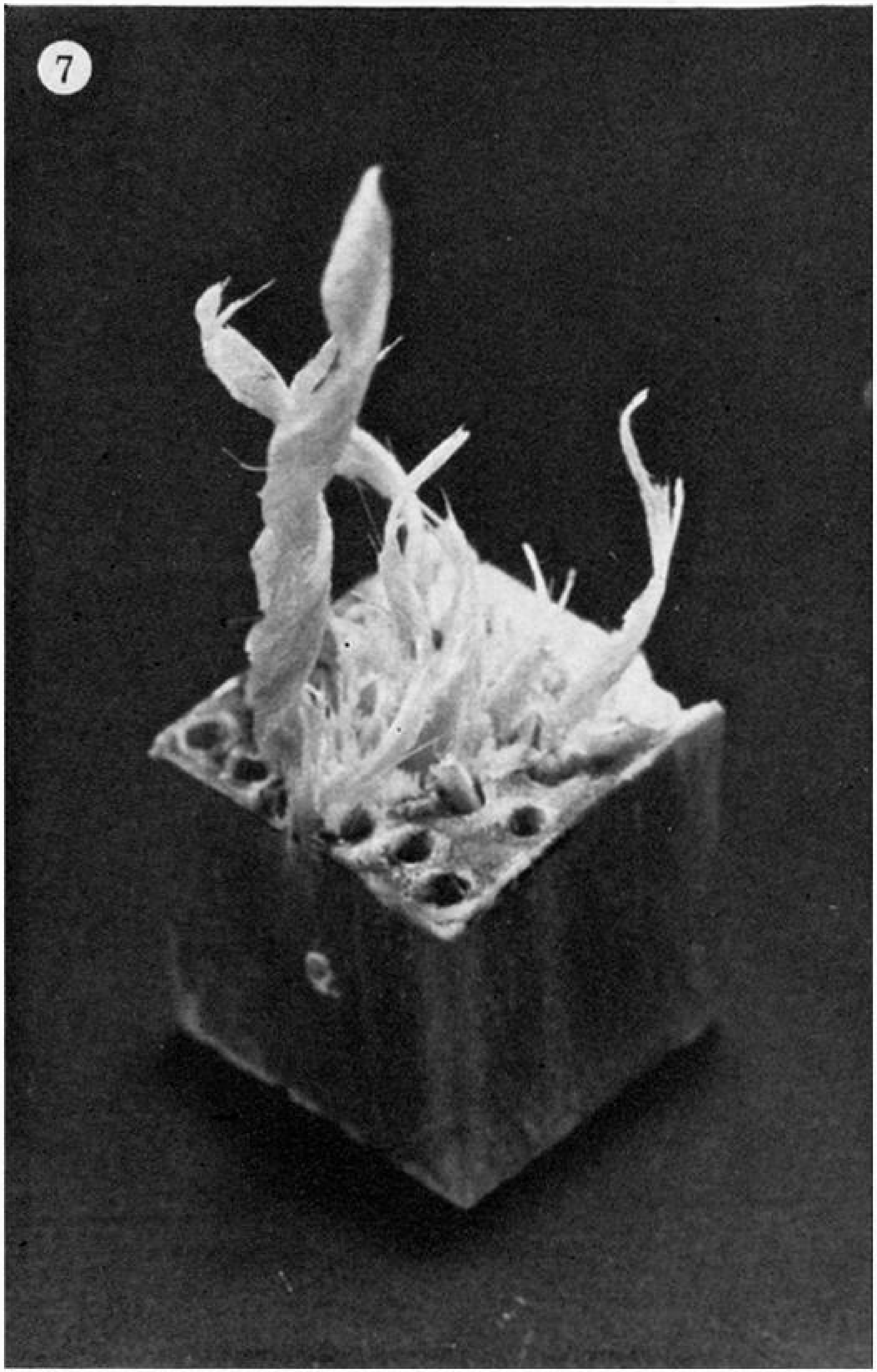
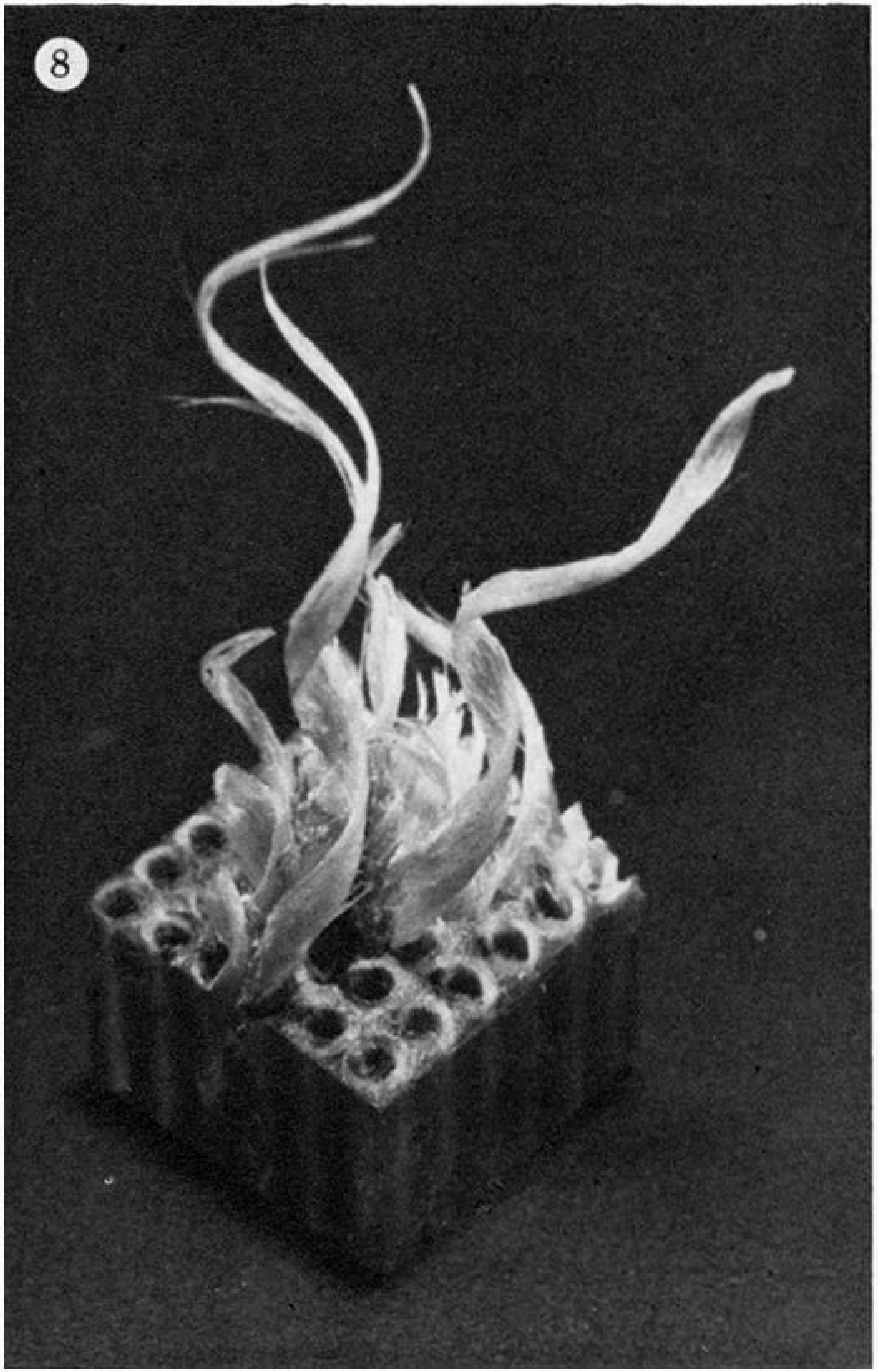


IGURE 6. Fracture morphology for composite reinforced with macrofibres of winding angle 15°. Bending fracture (magn. × 4).



IGURE 7. Fracture morphology for composite reinforced with macrofibres of winding angle 25°. Bending fracture (magn. × 4).



IGURE 8. Fracture morphology for composite reinforced with macrofibres of winding angle 35°. Bending fracture (magn. × 4).