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Influence of kink bands on the tensile strength of flax fibers

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Flax fibers, which originate from renewable resources, are an interesting alternative to mineral fibers. Their low cost, together with their low density, high specific rigidity and recyclability, constitute the major incentives for their use in composites. The parameters which have an important influence on the mechanical properties are [1]: the crystalline and amorphous elements, the degree of crystallinity, the spiral angle of the fibrils, the degree of polymerization, the porosity content, and the size of the lumen (a hollow core). Another parameter influencing the strength of fibers is the presence of defects, the topic of this text on flax fibers.

One general feature of natural fibers is their non-uniform, geometric characteristics. Flax fibers present a polygonal shape with 5 to 7 sides [2]. The longitudinal view of a fiber reveals a non-constant transverse dimension. The fibers are thicker nearer the root and become thinner nearer the tip. On average, a fiber is 19 μm in width and 33 mm in length [3]. It is, however, important to note the variation of the geometric dimensions, i.e., the transverse and longitudinal dimensions lie in the range of 5 to 76 μm and 4 to 77 mm, respectively. The flax fiber consists of highly crystalline cellulose fibrils spirally wound in a matrix of amorphous hemicellulose and lignin [4]. The fibrils are oriented with a tilt angle of 10–11° [3, 5] with respect to the axis of the fiber and hence display a unidirectional structure.

The cell walls of flax fibers contain numerous defects (cross marks), known variously as nodes, slip planes, kink bands, dislocations or micro-compressive defects. Fig. 1 shows examples, observed with a scanning electronic microscope (SEM), of kink bands at the surface of the fiber. These defects which are often at the same place on the various fibers of a bundle (Fig. 1), are easily observable by optical microscopy with polarized light, and correspond to the change of crystalline orientation [6]. Defects in fibers are produced irreversibly during the process of decortication by which the fibers are isolated from the plant [7]. The use of polarized light makes it possible to also detect other transverse marks, without deformation at the surface of the fiber, which manifest simply as a luminous strip corresponding to a very small change in the orientation of the fibrillary axis.

It is possible, with bending or compression loading, to create kink bands in virgin areas, as shown in Fig. 2. The morphology of these micro-compressive defects is reminiscent of the compression failure seen in unidirectional composites [8] and it is also similar to the kink bands formed in numerous highly oriented polymeric fibers (such as high modulus polyethylene) that fail under compression [9].

To ascertain if the number of defects is an important parameter in the tensile strength of industrial flax fibers, mechanical tests were carried out. Before tensile testing, the fibers were observed with an optical microscope using two methods: (1), observation under natural light of the shape of the fibers, variations in diameter, and the presence of kink bands, and (2) observation under polarized light. Defects exist throughout the length of the fibers (even in their extremities) and are non homogeneously distributed and gathered by groups of 1 to 15. The average length between two defects is about 101 μm ($\pm$39), without any correlation to the fiber diameter.

Tensile tests were carried out on 10 mm and 1mm unobstructed lengths of elementary flax fibers. The tensile behavior of flax fibers was measured using the standard method for a single material (NFT 25-704, ASTM D 3379-75), taking into account the compliance of the system. The load cell allowed measurements in the range of 0–2 N with an accuracy of 0.01%. The accuracy of the displacement measurement was $\pm$ one micron. For a length of 10 mm and an average diameter of 23 μm ($\pm$5.7), the tensile characteristics determined are: an average Young's modulus of 54 080 MPa ($\pm$15 128), an average tensile strength of 1339 MPa ($\pm$486), and an average elongation at the break of 3.27% ($\pm$0.84).

A length of 1 mm was chosen because: (1) it allowed a detailed analysis under the microscope of every fiber before tensile testing in order to ascertain the diameter, type of defects and distance between two defects, (2) the variation in fiber diameter is very low at this length, and (3) it is generally possible to examine the break area. This method allows us to establish the tensile strength only. Indeed, the low length of the fiber does not allow us to determine precisely the Young's modulus and elongation at the break. The average tensile strength was 1030 MPa ($\pm$383) but the average diameter was 26.6 μm ($\pm$6.8) for the 48 fibers tested. A correlation between the tensile strength and the fiber diameter is observed, i.e., when the fiber diameter increases, the tensile strength decreases (Fig. 3). For a length of 10 mm, the diameters lie between 14 μm and 40 μm and can be ranked in class of 2.5 μm width. For instance, the average tensile strength of the class 25–27.5 μm is 1060 MPa ($\pm$290).

The evolution of the tensile strength as a function of the number of defects by mm of fiber displayed in Fig. 4 does not show a straightforward relationship between the two parameters. Moreover, for a class of diameter,

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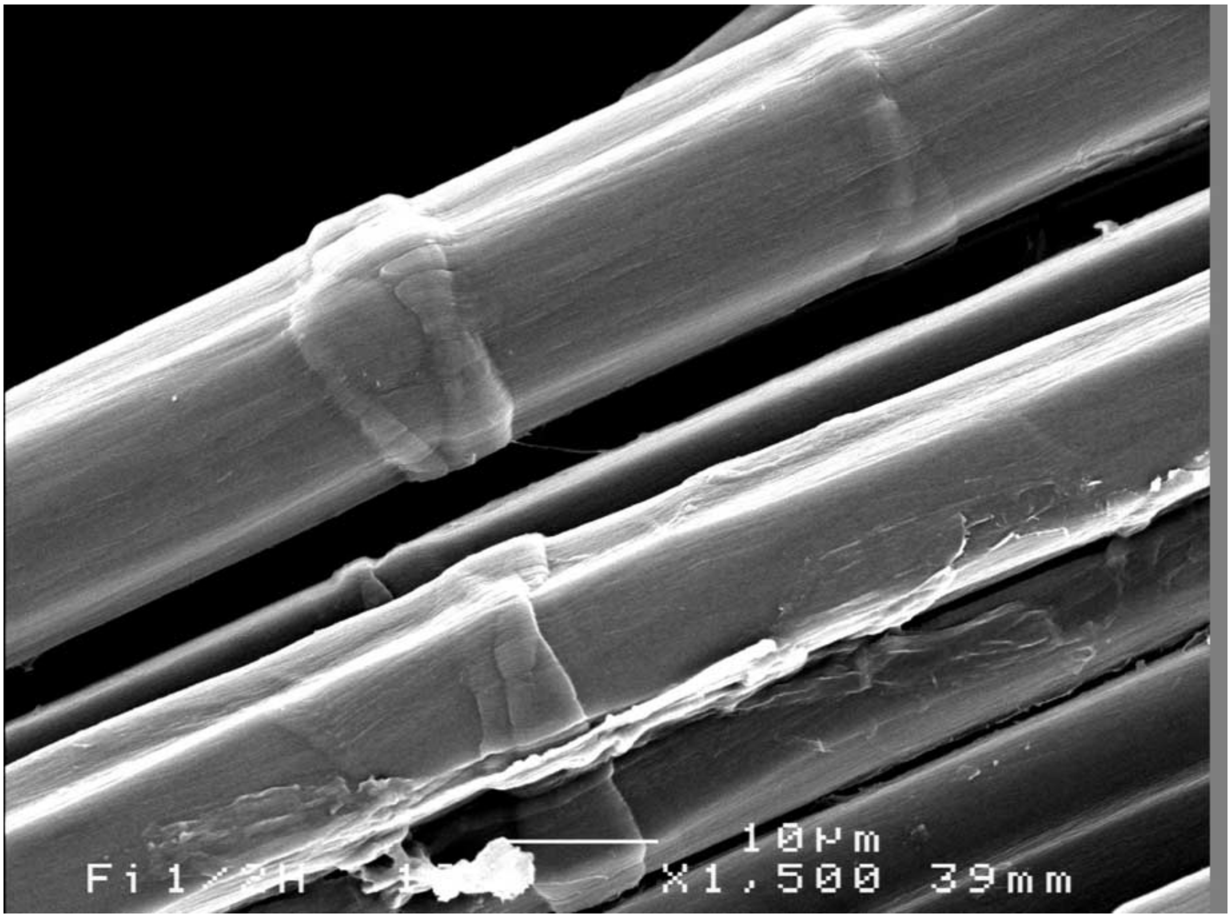

Figure 1 Flax fibers: Example of a bundle of flax fibers with kink bands in the same area.

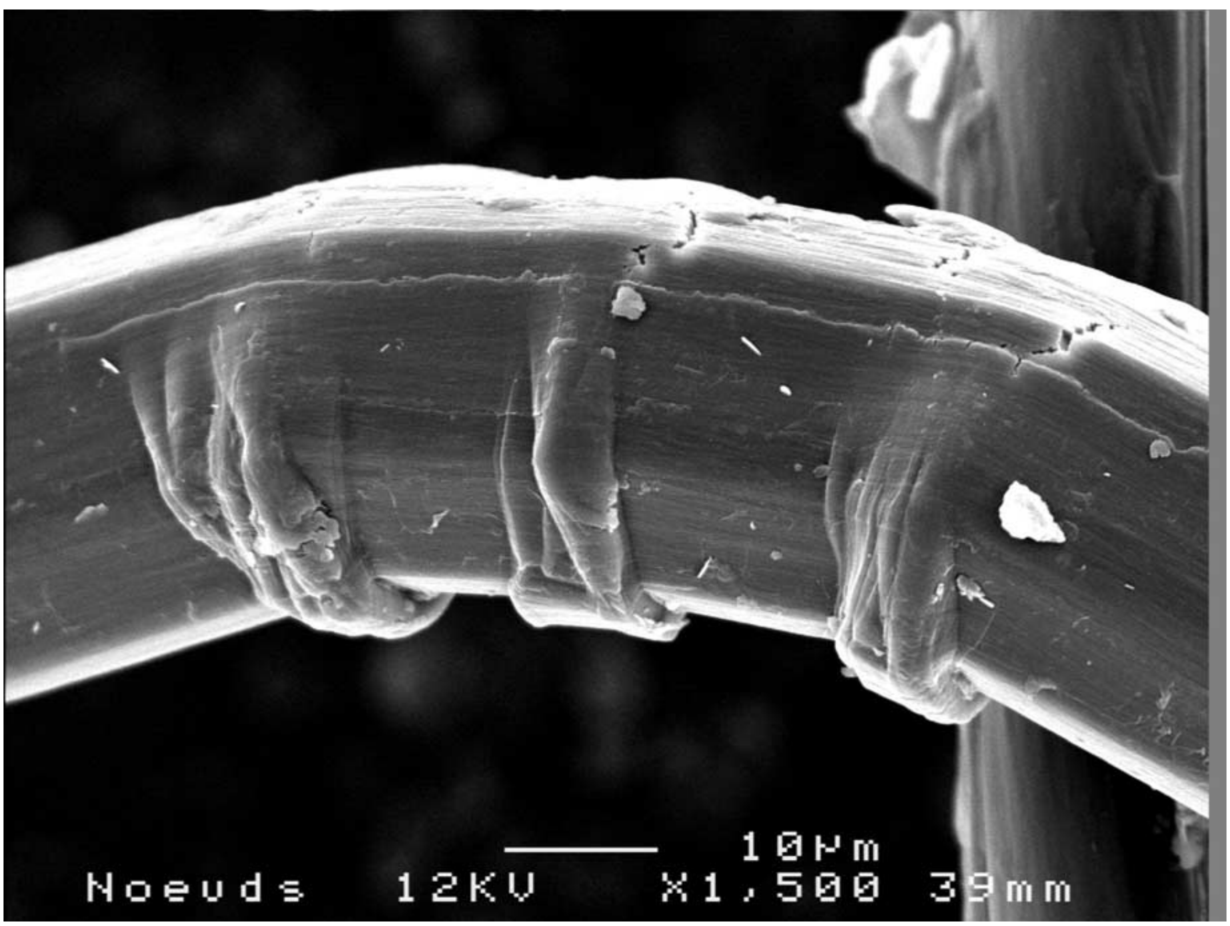

Figure 2 Bending of a flax fiber with buckling of cell walls.

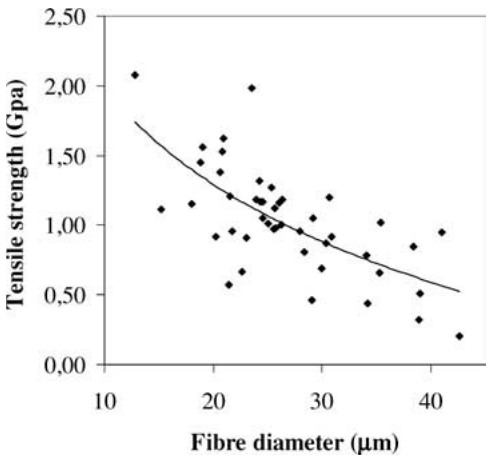

Figure 3 Tensile strength plotted as a function of the fiber diameter (L0 = 1 mm).

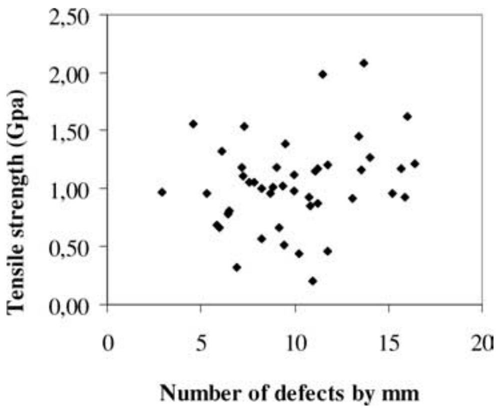

Figure 4 Tensile strength plotted as a function of the number of defects by mm of flax fiber.

there is no clear relationship between the kink band shape (X, V, simple strip) and tensile strength.

Kink bands would suggest a loss of tensile strength in the fiber. Carrying out tensile test in a SEM (Jeol JSM 6460LV) allows the *in-situ* monitoring of the kink band as being the most likely area to break. Fig. 5 shows the beginning of cracks in a flax fiber during a tensile test. The tensile stress is a function of the weakest link of a chain. Therefore the damage caused in the area of the kink band is the significant parameter. A flax fiber consists of a primary cell wall (about 0.2 μm) and a secondary cell wall. The layer S2 of the secondary cell wall essentially constitutes the bulk of the fiber. Microscopic observation does not allow one to know the damage arising in buried S2 layer.

For the application of flax fibers in high performance composites, the presence of these kink bands is not desirable because:

- The strength of the elementary fiber is an extremely important parameter.
- In a composite structure, the fiber kink bands are markedly geometric. It is believed that stress concentrations around micro-compressive defects can act as sites for the initiation of fiber-matrix debonding as well as for the formation of micro-cracks in the matrix [10].

For composite materials made with ultra-high-modulus polyethylene fibers and unsaturated polyester resin, the development of kink bands during the transformation is observed [9]. The mismatched thermal behavior of the fibers and matrix explains the compressive

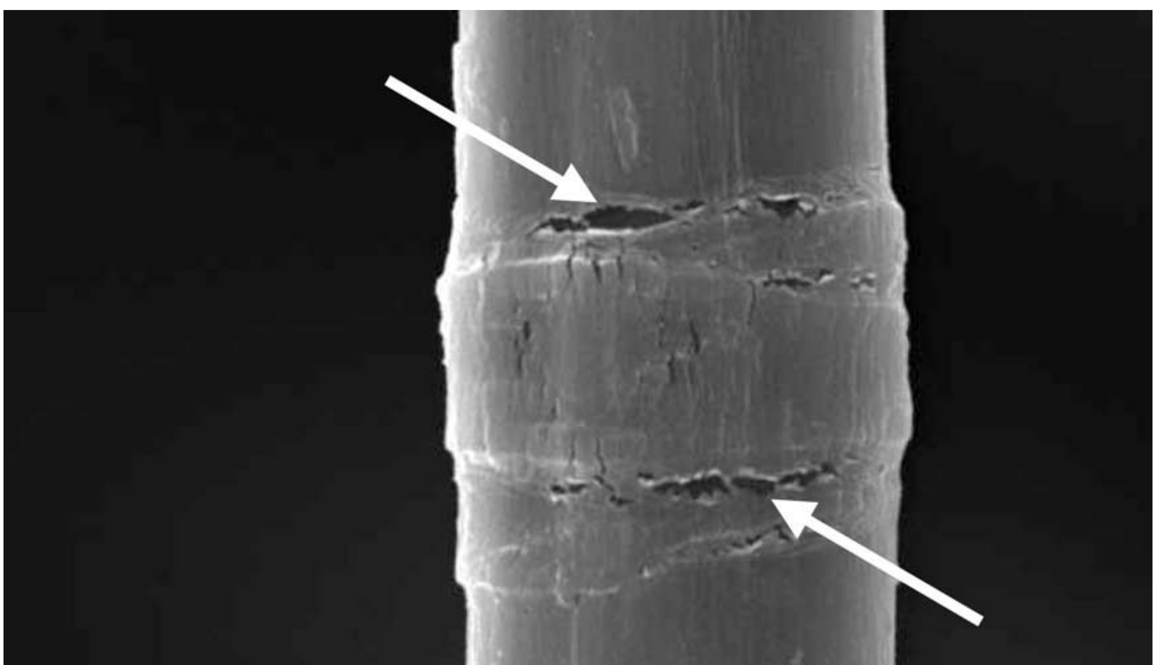

Figure 5 Tensile test in a scanning electron microscope. Start of cracks in a flax fiber in the area of a kink band.

buckling of fibers during cooling. This type of damage has not been observed in flax/polyester composite materials, which can forecast the achievement of high performances composites.

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