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PVDF microforce sensor for the measurement of Z-directional strength in paper fiber bonds

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ABSTRACT

The Z-directional strength of paper fiber bonds is an important parameter for the paper and board industry. The current methods of studying Z-directional paper fiber bond strength rely on handsheet measurements. This paper presents a novel tool for measuring the Z-directional strength of individual paper fiber bonds. A polyvinylidenefluoride (PVDF) film microforce sensor, with a special specimen holder, was designed, fabricated and calibrated to perform the measurements. The microforce sensor operates in a cantilever-like bending mode and is capable of measuring forces up to 10 mN. It is demonstrated that the output of our microforce sensor is linear, in addition to which it can measure forces higher than 3 mN with a coefficient of variation of less than 2%. This new microforce sensor was integrated into a microrobotic platform and is shown to be able to accurately measure the Z-directional bond strength of paper fibers.

1. Introduction

Paper fiber cells are typically 0.6–7 mm in length and 16–70 μm in diameter depending on their type [1,2]. Individual paper fiber bonds are the fundamental building blocks of paper and board products. The mechanical properties of paper and board materials at handsheet level are closely related to the mechanical properties of the individual fiber bonds [3,4]. In order to understand the mechanical behavior of paper and board networks, the individual fiber bonds have to be characterized in different loading modes. Most of the reported pulp and paper studies recognize four loading modes for the individual fiber bonds: shear or sliding mode, Z-directional or opening mode, torsional or tearing mode [5], and peeling mode [6] [see Fig. 1].

It is generally accepted in the paper industry that knowing the Z-directional strength of paper sheets [4] is of prime importance. For example, a low bonding strength results in delamination and splitting during printing and coating operations. In a paper mill, highly viscous materials are applied to the paper in the sizing presses, printers, coaters and laminators, during which, processes, the sheet can easily be pulled apart in the Z-direction. However, if the Z-directional bonding strength is too high, then some desirable properties such as opacity, folding stiffness and tear strength will be reduced [7]. All of the above make the measurement of the Z-directional strength of paper sheets, at both the handsheet level and at the level of the individual fiber bonds, a worthwhile area for research.

In recent years, various tools have been used to study the loading modes shown in Fig. 1 at the individual bond level. A load-cell based set-up for direct mechanical testing of fiber bonds in shear and tearing modes was reported in [5]. In another study, the shear mode in lap joints was tested with an Instron testing machine and a load elongation recorder [3]. A modified probe for an atomic force microscope has been used to measure the fiber bonding force in the peeling mode [8,9]. A microrobotic platform for making, manipulating and measuring the strength of individual paper fiber bonds in shear and peeling mode was developed and reported in [10–12].

The equipment for Z-directional testing at the handsheet level is very well developed and there are several commercial devices and methods [7] available to perform such tests, including the Lab Master® Z-direction tensile tester (Testing Machines, Inc., USA) and the L&W Z-direction tensile tester (Lorentzen & Wettre, Sweden). However, there is no device available in the market, or even reported in the literature, which is capable of the Z-directional tensile testing of individual paper fiber bonds. We are proposing a novel method for the Z-directional tensile testing of individual paper fiber bonds using a low-cost piezoelectric polymer sensor manufactured from polyvinylidenefluoride (PVDF) and operating in a cantilever-like bending mode. Hereafter the term “bending mode” refers to “cantilever-like bending mode”.

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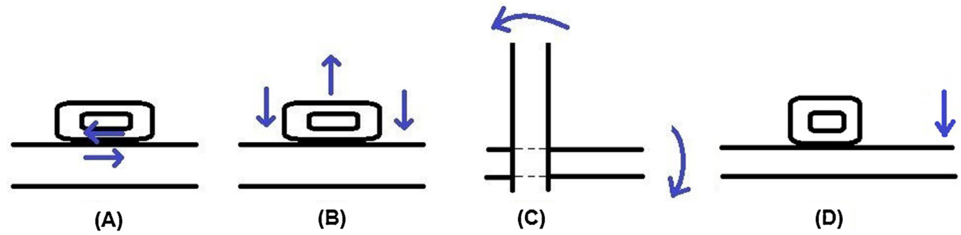

Fig. 1. Different modes of fiber bond loading. (A) Shear or sliding mode; (B) Z-directional or opening mode; (C) torsional or tearing mode; (D) peeling mode.

PVDF is a piezoelectric material having a solid and homogenous structure [13]. The operating principle of the PVDF film element is based on the piezoelectric effect; when an external force compresses or bends the film, an electrical signal is induced in the electrodes. PVDF is a semi-crystalline polymer material having a solid and homogenous structure [13]. The crystal polymorphs can be oriented in the manufacturing phase by stretching the film and poling it under a strong electric field, thus giving the PVDF film its piezoelectric and pyroelectric properties. Like other piezoelectric materials, the mechanical deformation of the poled PVDF film causes a change in the net dipole moment of the film, which in turn changes the internal electrical field of the film and induces a simultaneous surface charge in the electrodes on either side of the film. The charge sensitivity of a piezoelectric material is characterized by its piezoelectric coefficients, which are defined for each direction of the affecting force and the direction of the generated electrical field [14]. The piezoelectric coefficient d_{mn} is related to the electric field produced by mechanical stress [14]. The electrical flux density, D, of a PVDF sensor is defined as

$$D = \frac{Q}{A} = d_{mn}X_n = d_{3n}X_n, \quad (1)$$

where Q is the charge developed by the sensor, A is the conductive electrode area, d_{3n} is the piezoelectric coefficient for the axis of applied stress and X_n is the stress applied in the relevant direction [14]. For the electrical axis, m is always 3 since the electrodes are at the top and bottom of the film. For the mechanical axis, n can be 1, 2 or 3 since the stress can be applied to any of these axes. The piezoelectric coefficients provided by the manufacturer are $d_{33} = -33$ pC/N (compression) and $d_{31} = 23$ pC/N (stretching) [14]. In our application the electrical signal is mainly due to bending or stretching in 31-mode.

In the past recent years, several studies have been reported to measure micro- and milli-Newton forces in micromanipulation applications with sensors based on PVDF material. For instance, Fung et al. [15] showed that PVDF sensors can be used to sense micro-Newton forces when integrated with a commercial micromanipulator with a probe-tip. They demonstrated 1D and 2D sensing systems measuring the force when the probe-tip was used to lift a micro-mass. Similar approaches have also been proposed by Shen et al. [16,17]. In their work, a PVDF force sensor was used to measure forces occurring during micro-assembly [16] and micromanipulation [17], and they reported both high sensitivity, and a resolution in the range of sub-μN [16,17]. Kim et al. [18] utilized PVDF as a force sensor to detect the cell injection force. Their force-sensing instrument was calibrated with a reference load range from 0 to 1000 μN. Xie et al. [19] have also developed a PVDF injection force sensor. Kim et al. [20] developed a sensorized microgripper based on PVDF film sensor whose integrated force sensor was calibrated up to 6 mN and applied for the fine alignment tasks of micro-opto-electrical components. Sun et al. [21] have also developed a PVDF microforce sensor capable of measuring μN level forces.

This paper presents a PVDF film microforce sensor operating in a bending mode with a force range of up to 10 mN. The sensor is specifically designed, fabricated and calibrated to measure the Z-directional strength of individual paper fiber bonds. The resulting sensor is integrated into a microrobotic platform in order to demonstrate its function of measuring the Z-directional bond strength. For simplicity's sake, the term "fiber bond" will hereafter refer to an "individual paper fiber bond" in this paper.

2. Design and fabrication

The main component of our proposed force sensor is a PVDF element, in this case the LDT0-028K model (Measurement Specialties Inc., USA). The PVDF element is made of a 28 μm thick piezoelectric PVDF polymer film with screen-printed Ag-ink electrodes laminated between two 0.125 mm polyester substrate films.

Fig. 2 shows a schematic design of the sensor. Hereafter, the components in the figures are labeled "C.#-F.#", which refers to "Component Number-Figure Number". The sensor includes the following components: C.1-F.2 is the PVDF element; C.2-F.2 is a bond-holder with the bond samples mounted on its tip; C.3-F.2 is a connecting-element which fixes the bond-holder in place on top of the PVDF sensor; C.4-F.2 is a mounting-stage which is used for integrating the PVDF sensor into the microrobotic platform and C.5-F.2 represents an individual paper fiber bond.

Fig. 3A shows the implementation of the sensor; the component numbers are the same as in Fig. 2. The connecting-element and the bond-holder are shown in Fig. 3B and C, respectively. They were made from white Polylactide using a miniFactory® 3D-printer (miniFactory Oy Ltd., Finland). The extruded path is manually designed to be continuous, which improves the quality of the parts. The parts have ten 0.08 mm thick layers which are printed

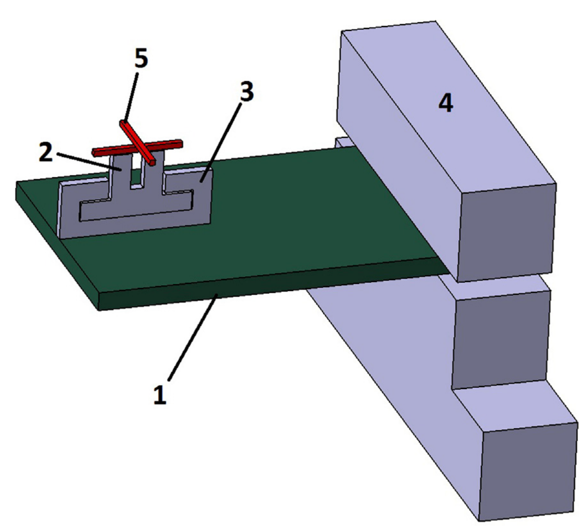

Fig. 2. Schematic design of the sensor: (1) PVDF element; (2) bond-holder; (3) connecting-element; (4) mounting-stage, and (5) individual paper fiber bond.