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Microrobotic Platform for Making, Manipulating and Breaking Individual Paper Fiber Bonds

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***Abstract*—This paper introduces a microrobotic platform to make, manipulate and break individual paper fiber bonds. An individual paper fiber bond is the construction unit of a paper sheet and its properties affect the strength of the entire network of a paper sheet. In one hand, conventional laboratory tests on paper fiber bonds are mainly performed in a hand-sheet level. On the other hand, reported methods for paper fiber bond strength tests in individual bond level are either direct which are manual, laborious and have a low throughput or indirect which require data interpretation. The microrobotic platform presented in this paper performs direct and individual tests on paper fiber bonds. Making, manipulating and breaking individual paper fiber bonds are accomplished successfully demonstrating the first steps towards individual bond strength measurement.**

I. INTRODUCTION

Wood fibers are cells having typical dimensions of 0.6 - 7 mm in lengths and 16 - 70 μm in diameters depending on their type [1]–[4]. An individual paper fiber bond is the construction unit of a paper sheet which is a network of wood fibers. Therefore, individual paper fiber bonds (IPFB)s [1] and their strength determine the key parameters affecting the quality of paper sheets.

Conventional methods for internal bond strength measurement of paper/board are mainly performed on a hand-sheet level. They include static methods, e.g. Z-directional tensile test and shear cohesion test; and dynamic methods, e.g. Scott bond test [5]. Even though the results of such tests on hand-sheets are highly correlated to the internal bond strength of paper/board, all of them include undesirable information in their results which are not decoupleable. For example: the Z-directional tensile test encompasses both intra- and inter-fiber bonding energies, the shear cohesion test combines the force required to shear the bond with the force acting on the plane of the sheet, and the Scott bond test over evaluates the bond strength because of its dynamic nature [5].

Studies on indirect bond strength measurements both in bulk amount and in individual level have been reported. Indirect methods are mainly optical and based on light scattering e.g. correlating specific scattering coefficient with Young's modulus and bonded area of hand-sheets [6], or correlating individual bonded area with individual bond strength [7].

Direct IPFB characterization methods date back to early nineties [8] when the second generation of the IPC load-elongation recorder developed in sixties by K.W. Hardacker [9] was used. However, the method is very laborious and low throughput.

Recent advances in microrobotics and microsystems technology provide new tools and methods to manipulate and characterize micro- and nanoscale samples such as living cells [10]–[15] and carbon nanotubes [16], [17], and also promote microassambly approaches [18]–[21]. Aforementioned advances in microrobotics and microsystems technology provide new means to develop IPFB manipulation and characterization methods. It is possible to break an IPFB in two directions: normal to the bonded area (Z-direction) or parallel to the bonded are (Shear-Mode). The Z-direction bond strength and the shear bond strength are important factors for the board-making and paper-making industries, respectively. The focus of this study is on breaking the IPFBs in the shear-mode.

To break an IPFB in the shear-mode, two sets of forces need to be overcome: bending the crossed-fiber, F_{bcf}, and breaking the bond, F_{bb}. Fig. 1 illustrates the forces involved in breaking an IPFB in the shear-mode. A microrobotic platform for manipulation and flexibility measurement of individual paper fibers (IPF)s [1] has been developed and experiments to measure F_{bcf} was demonstrated in the previous step of this study [22]. This paper presents a microrobotic platform

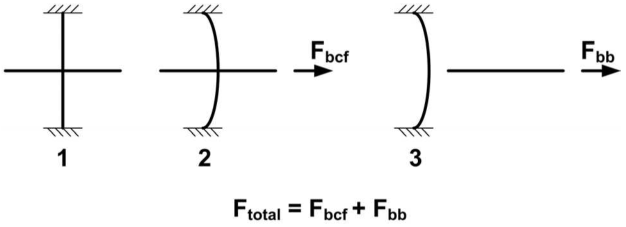

Fig. 1. Illustration of forces involved in breaking of an IPFB in Shear-Mode. 1) Schematic of an IPFB. 2) Force required to bend the crossed-fiber F_{bcf}. 3) Force required to break the IPFB F_{bb}.

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[1] In this paper the abbreviation IPF stands for Individual Paper Fiber and IPFB stands for Individual Paper Fiber Bond, respectively.

for making, manipulating and breaking IPFBs which are the primary phases in measurement of individual paper fiber bond strengths, F_{bb}. The platform provides an infrastructure for automated IPFB strength characterization to measure the bond strength directly and to provide statistically reliable data in high throughput.

The rest of the paper is organized as follows: Section II describes the design and implementation of the platform; Section III models the robotic processes for making, manipulating and breaking IPFBs; Sections IV and V describe the performed experiments on making, manipulating and breaking the IPFBs, and also the results of the experiments, respectively. Finally, Section VI encompasses the conclusions and discussions.

II. DESIGN AND IMPLEMENTATION

The architecture of the platform is illustrated in Fig. 2. It presents six main functions: sample storage (F1), micromanipulation (F2), force sensing (F3), visualization (F4), dispensing (F5) and control (F6). The platform also prepares samples for other instruments, e.g. an atomic force microscope or a scanning electron microscope. Each function is divided to sub-functions and those for micromanipulation (F2) and dispensing (F5) are discussed in this section in details. The tasks of sample storage (F1), visualization (F4) and control (F6) functions are similar to tasks in paper fiber flexibility measurements [22] and therefore are not discussed here.

Micromanipulation function (F2) enables micropositioning, micro-orienting and microgripping of the paper fibers. The micropositioning sub-function is used for placing the area of interest, a fiber-bank, a rotary table or an IPFB-holder in the working space of microgrippers. Micro-orienting sub-function facilitates the change of the fiber or bond orientation; and microgripping sub-function performs the grasping and handling of fibers and bonds. Micromanipulation is also used for moving the dispenser and aligning the dispenser tip on the required targets to shoot droplets of various liquids.

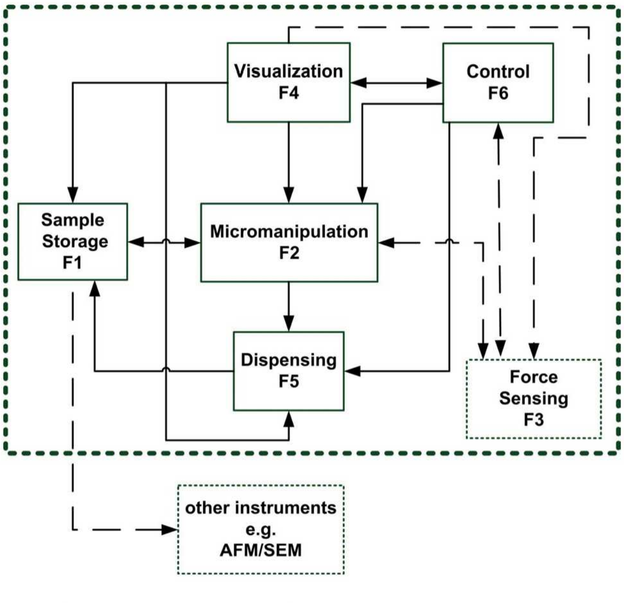

Fig. 2. Conceptual design of a microrobotic platform for making, manipulating and breaking IPFBs - Main Functions.

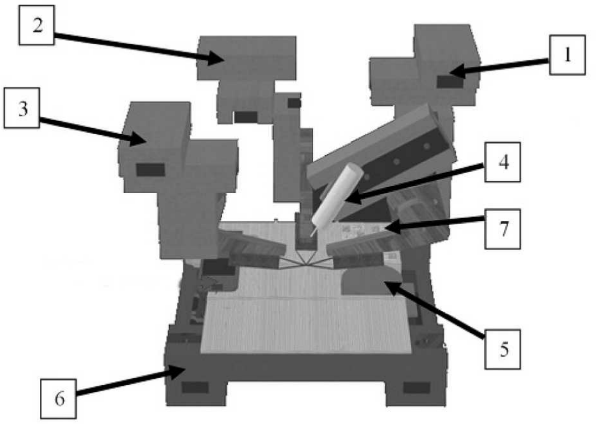

Fig. 3. 3D Design of IPFB manipulation and characterization platform. 1) 5-DOF Microgripper, 2 & 3) 4-DOF Microgripper, 4) Dispenser, 5) Rotary-Table, 6) 2-DOF Micropositioner (XY-table), 7) Fiber-Bank.

Hydrogen bonding is one of the primary mechanisms by which papermaking fibers bond to each other. Cellulose and hemicellulose of paper fiber walls are covered with hydroxyl groups. Therefore, water is essential in the process of making the paper fiber bonds [23]–[26]. Dispensing function (F5) enables shooting droplets in nanoliter scale on the cross-point of two IPFs to initiate the hydrogen bonding. It can also shoot droplets of other chemicals on the IPFs or the IPFBs to investigate the effect of those chemicals on bonding capabilities of fibers.

The force sensing function (F3) measures the magnitude of force required to break an IPFB, F_{bb}. This function is not yet implemented in the microrobotic platform and will be reported in coming studies.

Fig. 3 shows the Stacked Gantry Crane configuration of the platform. In this configuration, there are one tailored 5DOF

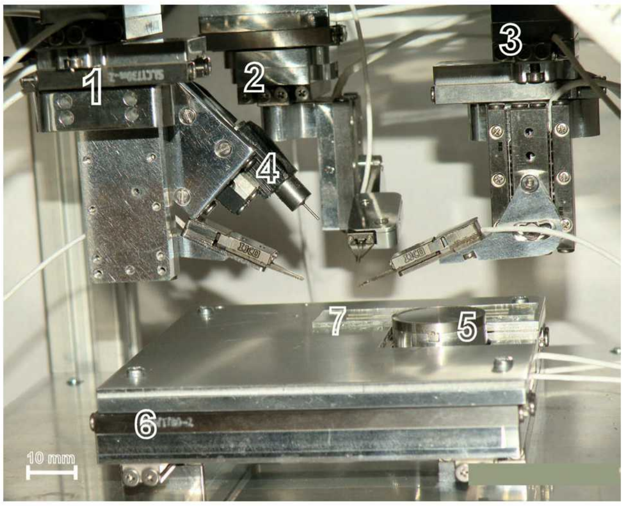

Fig. 4. Implementation of the platform. Numbering is same as in Fig. 3

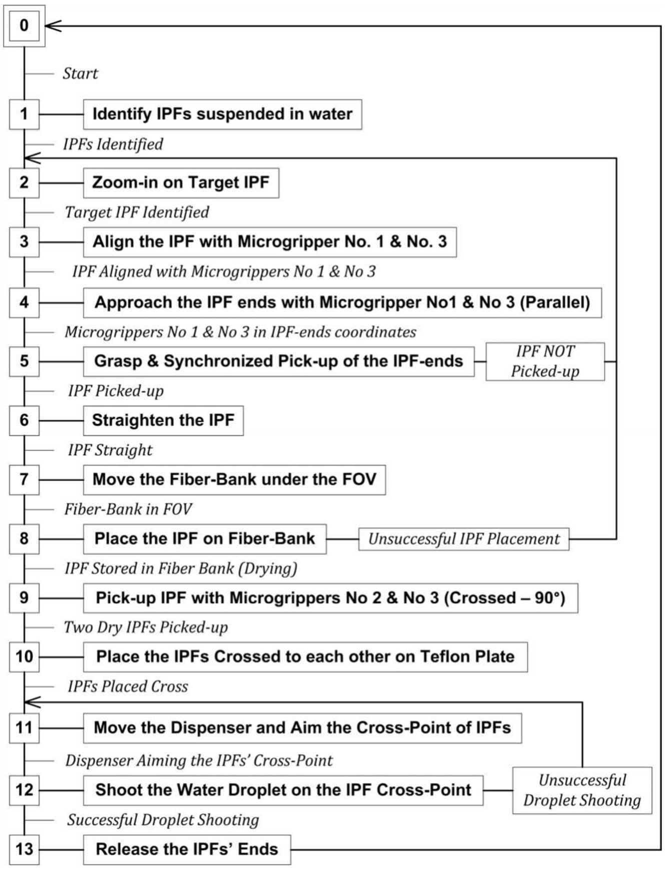

Fig. 5. Sequential function chart of making IPFBs.

(Microgripper-1), and two tailored 4DOF (Microgrippers-2 & -3) micromanipulators from SmarAct Co. The 4DOF micromanipulator includes three positioners in X, Y and Z directions and the microgripper. In addition to the XYZ-positioners and the microgripper, the 5DOF unit includes a positioner for the dispenser (4) (Lee Co.). The platform includes also an XY-table (6) of SmarAct Co. A rotary-table (SR-1908 of SmarAct) (5) and a self-made fiber-bank (7) are mounted on the top of the XY-table. The fiber-bank is made of SU-8, a common epoxy-based negative photoresist polymer used in lithography, with the height of 200 μm. The fiber-bank is a place to store and sort the fibers based on their dimensions. Fig 4 shows the current implementation of the platform.

III. MODELING OF ROBOTIC PROCESSES FOR MAKING, MANIPULATING AND BREAKING IPFBS

This section discusses modeling of robotic processes for making, manipulating and breaking IPFBs. The potential applicable tasks of the platform on fibers or bonds are as follows: identifying, zooming in or out, orienting or aligning, grasping, synchronized grasping, placing, moving, releasing and shooting droplets. This section combines the mentioned tasks to create a specific sequential chart for making, manipulating and breaking IPFB processes as illustrated in Fig. 5, Fig. 6 and Fig. 7, respectively. The advantage of these sequential charts is not only achieving the desired goals in a tele-operated mode but they are also used for designing the control system for automating these processes.

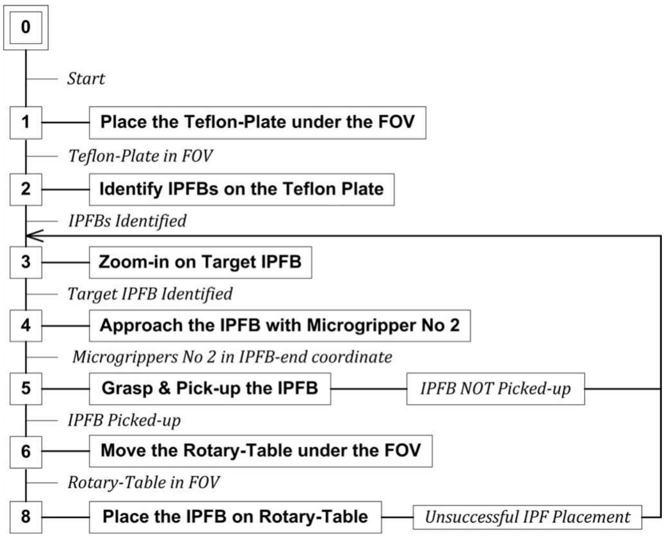

Fig. 6. Sequential function chart of manipulating IPFBs.

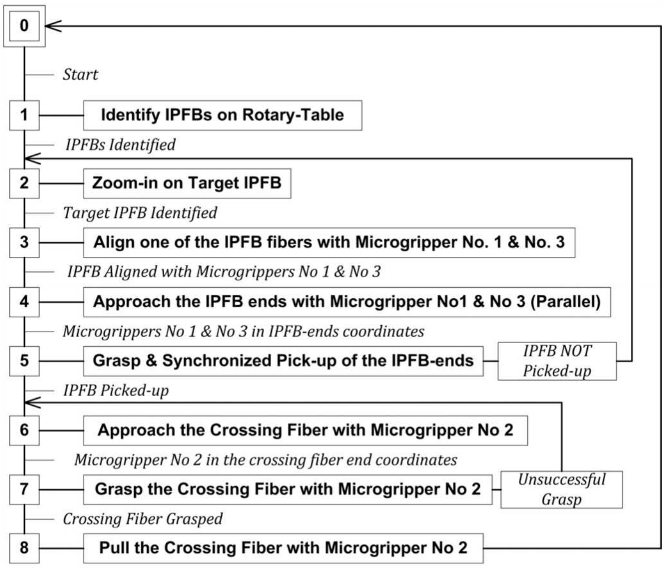

Fig. 7. Sequential function chart of breaking IPFBs.

IV. EXPERIMENTS

This section discusses experiments performed for making, manipulating and breaking of individual paper fiber bonds. The fiber sample used in this study is *softwood kraft pulp* received from ING-Pagora-Grenoble.

A. Making Bonds

There are two important parameters in determining bonded area between two paper fibers, crossing angle, α, and vertical angle, β. The crossing angle affects directly the bonded area [See Fig. 8]. Equation 1 shows the relation between the crossing angle, α, with the calculated area of a fiber bond,

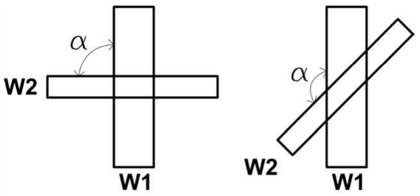

Fig. 8. Crossing Angle of Fiber-Fiber Bond (α) [7].

A_{calc}:

$$A_{calc} = W1 \times W2/sin(\alpha) \tag{1}$$

where $W1$ and $W2$ are the thicknesses of the IPFs [7].

The vertical angle is the angle between the fiber axis and the image plane. If the main fiber axis and the image plane are not perpendicular, the apparent fiber cross sectional area in the image is larger than the real area. The vertical angle, β, approximates the angle between image plane and main fiber axis [7].

In a current IPFB making method, a highly dilute suspension of fibers are prepared and the droplets of suspension are placed between two Teflon plates and then the plates are dried for 45 minutes [7]. The randomly oriented IPFs in this method leads to random α and β angles. Fig. 9 shows few examples of possible artifacts caused by conventional Fiber-Fiber bond making methods.

The microrobotic platform presented in this paper is able to make artifact-free IPFBs by following the sequential chart presented in Fig. 5. The disintegrated paper fibers are placed on the rotary-table using a pipette. The operator identifies the IPFs in the suspension using the vision system, and selects one of them as a target. Then he aligns the target IPF with Microgripper-1 and Microgripper-3 [See Fig. 4]. The platform picks disintegrated paper fibers from the rotary-table by synchronizing the Microgripper-1 and Microgripper-3; straightens the paper fibers, and sorts and places them on the fiber-bank for drying. Next, the platform picks the IPFs one by one [See Fig. 10 - a], and places them crossed to each other on a Teflon-plate [See Fig. 10 - b]. Two strategies for making the IPFBs are tested: wet-pressing and dry-pressing of the crossed fibers.

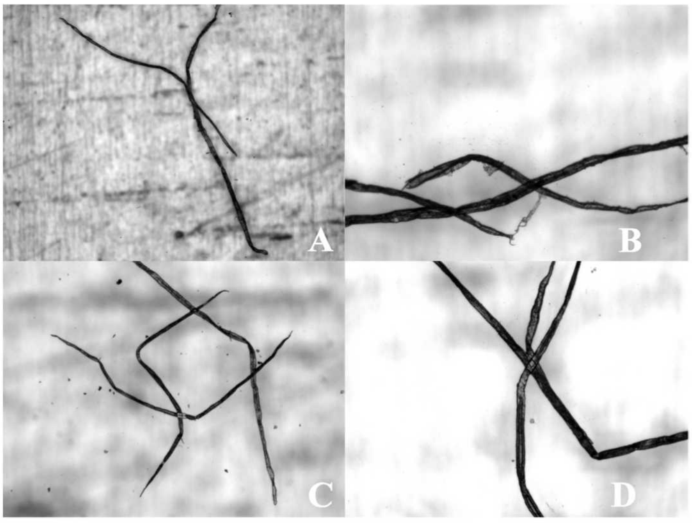

Fig. 9. Artifacts caused by conventional Fiber-Fiber bond making methods. A) Random (α & β) angles, B & C) More than one bond on one fiber, D) Two bonds on the top of each other.

1) Wet-Pressing: Water, heat and pressure are necessary factors to make a bond between two paper fibers. The dispenser shoots a droplet of water on the cross-point of two fibers [See Fig. 10 - b, c]. Another Teflon-plate is used to cover the bottom one, and the plates are placed in an oven for 45 minutes at 70°C under 140 kN/m^2 pressure to bond the crossing fibers together [See Fig. 10 - d].

2) Dry-Pressing: Microscale-mechanical-interlocking of paper fibers (the same mechanism as Velcro fastener in macroscale) plays a role in bonding of two fibers together in addition to other bonding mechanisms such as hydrogen bonding and interdiffusion of micro/nano-fibrils [27]. The hypothesis tested here is to bond fibers with microscale-mechanical-interlocking mechanism in a dry state. To check this hypothesis, the aforementioned bonding procedure was performed excluding shooting the droplets of water.

B. Manipulating Bonds

Bond manipulation is performed in two steps: transferring the IPFBs from the Teflon-plate to the rotary-table (Step-1), and transferring the IPFBs from the rotary-table to the bond breaking stage (Step-2).

After baking the bonds, the Teflon-plate is taken from the oven and placed under the field-of-view (FOV) of the vision system. The operator identifies the IPFBs on the Teflon-plate; selects one and zooms-in on the target IPFB. Microgripper-2 approaches the IPFB, grasps it and picks it up. Then, the

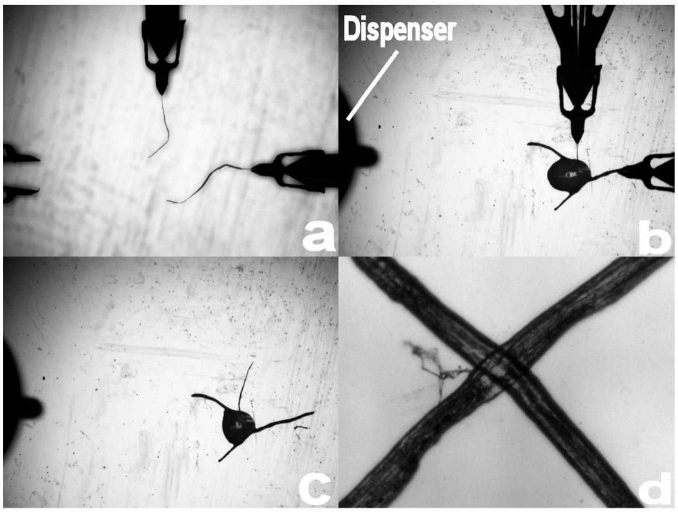

Fig. 10. Process of making and IPFB. a) Pick-up IPFs, b) Place the IPFs perpendicular to each other on a Teflon-plate and shoot a droplet of water on the crossing point by using the dispenser, c) Move-out the microgrippers, – and then cover the bottom the Teflon-plate with another Teflon-plate, and baking in an oven for 45 minutes at 70°C under 140 kN/m^2 pressure – d) The produced IPFB.

rotary-table moves under the FOV and the IPFB is placed on the rotary-table. Fig. 6 illustrates the sequential chart of the first step of IPFB manipulation. The second step of the IPFB manipulation is a part of IPFB breaking process [See Fig. 7].

C. Breaking Bonds

Fig. 11 shows the experimental process of breaking an IPFB explained in Fig. 7 in the sequential function chart format. An IPFB on the rotary-table is first identified (Fig. 11-a) and rotary-table aligns the IPFB with the two parallel axis Microgripper-1 and Microgripper-3. Synchronized Microgripper-1 and Microgripper-3 grasp the two ends of the IPFB and lift it above the rotary-table (Fig. 11-b, c). The Microgripper-2 perpendicular to the other two microgrippers is used for grasping the crossing fiber (Fig. 11-d). After a secure grasp, it pulls the crossing fiber until the bond breaks (Fig. 11-e, f).

V. RESULTS

Making the IPFBs in presence of water was successful, but bonding paper fibers in absence of water was not possible. This shows that microscale-mechanical-interlocking of paper fibers is either not possible or not sufficiently strong without water to create a bond between two fibers.

The platform can minimize the artifacts of conventional bond making processes. Since the IPFBs are made with the assistance of the microrobotic platform, there is absolutely no random crossing angle, α. The IPFBs made in the experiments have the desirable crossing angle, α, close to 90° and also desirable vertical angle, β, close to zero. As the IPFBs are made one by one, there are only one bonded area per each pair of fiber.

Moving the IPFBs from the Teflon-plate to the rotary-table and orienting the IPFBs was demonstrated. Finally, breaking the IPFBs were accomplished as planned and the process was demonstrated.

The aforementioned tele-operated experiments are satisfyingly repeatable. The focusing and defocussing tasks to acquire the Z-direction coordinates of IPFs and IPFBs is the major bottleneck in speeding up the processes. Using a side-view in addition to the current top-view can effectively increase the throughput of the microrobotic platform.

The results and experience gathered during this paper are very valuable information on automating the mirorobotic platform.

VI. CONCLUSIONS AND DISCUSSIONS

A microrobotic platform to make, manipulate and break IPFBs was designed and fabricated. The platform picks IPFs form water suspension, and sorts and places them on a fiber-bank. The platform picks the fibers one by one and places them crossing each other to make the individual bonds. The platform grasps and manipulates the IPFB using two microgrippers, and finally breaks the bond using a third microgripper.

The quality controlled IPFBs - which have desirable α and β angles - can help the paper fiber scientists to achieve better results in their experiments, and therefore understanding and analyzing the true nature of bonding mechanisms between two IPFs better than before.

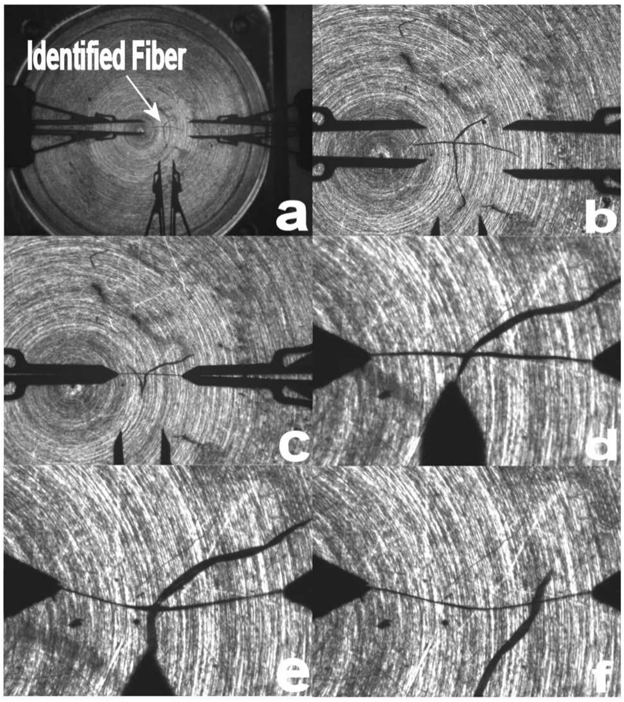

Fig. 11. Process of manipulating and breaking an IPFB. a) Identifying an IPFB, b) Grasping the two ends of the IPFB, c) Lifting the IPFB above the rotary-table, d) Grasping the crossing fiber, e) Pulling the crossing fiber, f) Breaking the IPFB.

Making, manipulating and breaking an IPFB was demonstrated successfully which is the first step towards individual bond strength measurement. A force sensor will be integrated in the crossing microgripper in future to perform the IPFB strength measurement. The platform provides an infrastructure to develop an automated individual paper fiber bond manipulation and characterization platform which provides statistically reliable data about IPFBs in high throughput.

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