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Improvement of the mechanical performance and dyeing ability of bamboo fiber by atmospheric pressure air plasma treatment

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Abstract

Atmospheric pressure air plasma was applied for treatment of different kinds of natural bamboo fiber to improve their mechanical properties and surface characteristics, which are suitable for adhesion and dyeing. The tensile strength and Young modulus of bamboo fiber were significantly improved; SEM and AFM study show that the surface of fiber became cleaner and rougher after plasma treatment. Plasma treatment caused the cracking, removing of the protective skin of alkali-untreated fiber and etching to form a cleaner and rougher surface. The dyeability of both groups of bamboo fiber which are used for composite and textile purposes is significantly enhanced after treatment.

KEY WORTS: bamboo fiber, atmospheric air plasma treatment, tensile strength, roughness

1. INTRODUCTION

In Vietnam, bamboo is one of the most abundant and sustainable natural resource with the record of 102 species with 19 geneses of bamboo family. Bamboo fiber, which is widely available in the nature as mentioned above, is one type of cellulose fiber with many advantages such as low density, low cost, acceptable mechanical properties and enhanced energy recovery. Like other cellulose fibers, bamboo fiber can be totally degradable and is therefore environment-friendly. Due to these facts, there is a good potential to use bamboo fiber to get a motivated combination of environment-friendliness and economical feasibility. Two of the significant new potential application fields of the bamboo fiber are strengthening fiber in polymer composite and textile material. Polymer composite based on natural bamboo fiber is refereed as the *green composite* and is a potential replacement for the un-degradable glass-fiber polymer composite. As the textile fiber and yarn, bamboo materials are particularly attractive as they meet the high comfort and aesthetic standards of the modern consumer. They have excellent moisture absorption and releasing property because the cross-section of the bamboo fiber is filled with various micro-gabs and micro-holes. The most unique property of bamboo fiber is its natural function of anti-bacteria, bacteriostatic and deodorization. On the other hand, bamboo fiber has high cellulose crystallinity causing processing difficulty and in polymer composite they show a week interfacial adhesion to resin. In both above applications, the hydrophilic property of fiber is very important for many processes, such as dyeing, or wetting for a good adhesion. Compared with some other natural fibers, the dyeability of bamboo fiber is not good enough. Improvement of the hydrophilicity of the fiber surface can lead to the improvement of the dyeing ability and the better adhesion [1, 2, 3, 4, 5].

In recent years, cold plasma technology, which is a dry and environment friendly process, is considered as a promising treatment method for modification of the fiber surface, including the natural fiber. Most previous research related to low-pressure plasma for fiber surface modification [6, 7]. However, in the treatment at low-pressure, to initiate and maintain plasma discharge requires expensive vacuum system and productivity is therefore low. To avoid these drawbacks, atmospheric pressure plasma discharge has been proposed and created. Treatment at atmospheric pressure and air as the gas can be more easily applied to practical production-line operation .

In this study, high radio frequency plasma discharge was used to modify the surface of various kinds of bamboo fiber to enhance the mechanical and surface property for wetting and dyeing purpose.

2. EXPERIMENTAL

Materials

Three types of bamboo fiber were used for this study:

Bamboo I: Fiber extracted from *Dedrocalamus membranaceus* Munro (Luong in Vietnamese), the most popular bamboo in Vietnam, used for polymer composite and other purpose, extracted by steam explosion technique, alkali-untreated.

Bamboo II: Fiber extracted from bamboo *Dedrocalamus membranaceus* Munro, extracted by mechanical technique, alkali-treated.

Bamboo III: Fiber from bamboo *Neohouzeaua dullooa* (Nua in Vietnamese), the cheapest bamboo in Vietnam, used for polymer composite and other purpose, extracted by mechanical method, alkali treated.

All above three bamboo fiber samples were produced by National Key Lab of Polymer & Composite Material, Hanoi University of Technology.

Bamboo IV: Natural bamboo fiber for textile from China with a fineness of 6.01 dtex

Plasma treatment

Fig.1 shows the schematic diagram of the experiment system used to study.

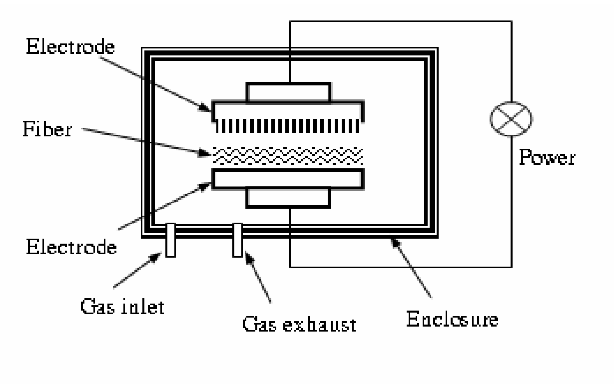


Figure.1: Experimental plasma system

The major structural components of the plasma device for this study are a bell (chamber) and an excitation source connecting with gas line. Bamboo fibers reside directly in the chamber housing the plasma. Air is used as gas. Plasma excitation sources in this test having high frequency of 17.5 KHz with the plasma power of from 100 W to 150 W. The investigation was carried out at room temperature, atmospheric pressure with air as the gas.

Tensile test of fiber

Bamboo I, II and III were cut approximately 20 mm in length. Both fiber ends were glued on the pieces of paper (paper tabs of size 10x10 mm^2) for handing purposes. During pulling, the specimens were handled only by paper tabs and the working zone of the fiber was not touched. Before experimenting, fiber diameter was measured on optical microscope with an optical objective of 4-40 times magnification. The test was carried out on a computer connected LLOYD LRX Plus machine. Measurements of load and displacement were used to compute stress strain curves for the fibers. All tests were displacement controlled with the displacement controlled with the loading rate of 2 mm/min.

Bamboo IV was measured in mechanical properties such as tensile property and elongation to break using a Pensilon AND RTC-125A in a standard laboratory condition.

Fiber weight loss

Percent weight loss (PWL) is used to determine the etching of the plasma to fiber. The PWL after plasma treatment is determined by the following formula:

$$PWL = \frac{W_p - W_o}{W_o} \times 100\%$$

where W_o is the weight of untreated sample and W_p is the weight of plasma treated sample.

Surface morphology and contact angle

JEOL JMS 5300, JEOL JMS 6360LV and the Atomic Force Microscopy AFM PSIA XE-100 were used to study the morphology changes of the fiber surface caused by plasma treatment. The contact angle was measured by a Thermo Cahn RADIAN 300 (US).

Dyeing and dyeing rate

For dyeing natural bamboo fiber, an aqueous solution containing 3% on the weight of fiber of direct dye and 10% of sodium chloride were employed. The liquor ratio was 1:30. The temperature was increased from 40 to 100^{o}C, keep for 1 h, then cool down to 50^{o}C. After dyeing fibers were washed and dried. The absorbance of the dyeing solution before and after dyeing was measured by a Model 721 visible spectrophotometer. The dyeing rate is calculated by following formula:

$$\text{Dyeing rate (\%)} = (1-C_i/C_o) \times 100\%$$

where C_o and C_i are the absorbance of dyeing solution before and after plasma treatment.

3. RESULTS AND DISCUSSION

Mechanical properties

The tensile strength and tensile modulus of the bamboo fiber I, II and III after plasma treatment at atmospheric pressure with various treatment times were presented in Fig. 2 and Fig. 3.

It can be seen that the suitable treatment time for Bamboo I and II is 5 min. while for Bamboo III only 4 min. For all three fibers Bamboo I, II and III, plasma treatment can remarkably improve the tensile strength, 15.5% at Bamboo III after 4 min treatment, 34% at bamboo II after 5 min, respectively. Young modulus also significant increased showing a higher stiffness of treated fiber.

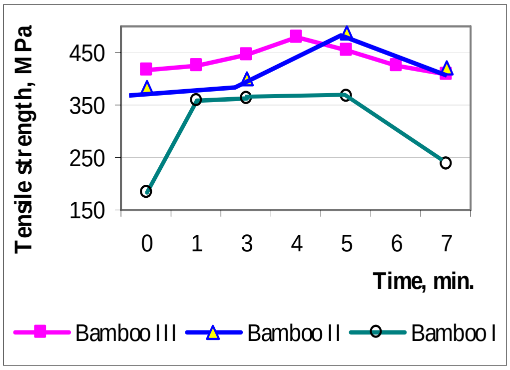


Fig.2: Tensile strength of bamboo fibers for polymer composite purpose vs. treatment time at power 100W

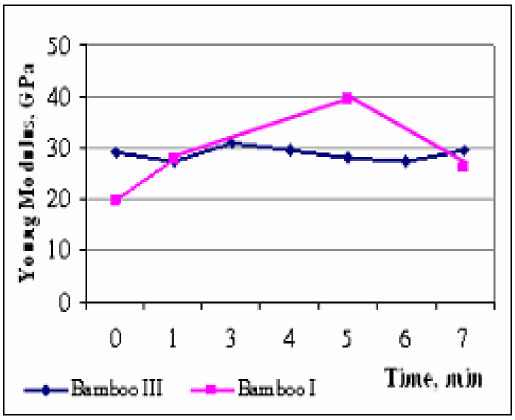


Fig.3. Young modulus of bamboo fibers for polymer composite purpose vs. treatment time at power 100 W

Especially, the tensile strength and Young modulus of Bamboo I, which is alkali-untreated after extracted, increased for more than double after 5 minutes treatment. It can be explained that the charged particles bombarded the fiber surface causing the etching and removing the impurity of bamboo fiber such as lignin, hemi-cellulose, making the diameter of fiber smaller. All of that can cause the improvement of tensile strength. When producing plasma, there are not only charged and neutral particles bombarding samples, but it also produced light, such as UV light which may cause a slightly improvement of the cellulose crystallinity, making a significant increasing in Young modulus.

In Table 1, the mechanical properties of Bamboo VI before and after plasma treatment are presented.

After plasma treatment, the mean tendency of Bamboo IV increased for 18.9% while the mean elongation decreased 7.2%, respectively. Similarly to the case of Bamboo I, II and III, plasma might increase of the rigidity leading to the decrease of elongation of Bamboo IV.

Table 1: Some mechanical properties of Bamboo IV, treated at 100 W

	Un-treated	3 min treated
Mean tenacity cN/dtex	4.75	5.64
Mean Elongation, %	3.61	3.35

Percent weight loss PWL

The weight loss of Bamboo III and Bamboo IV are showed in the figure 4 and table 2.

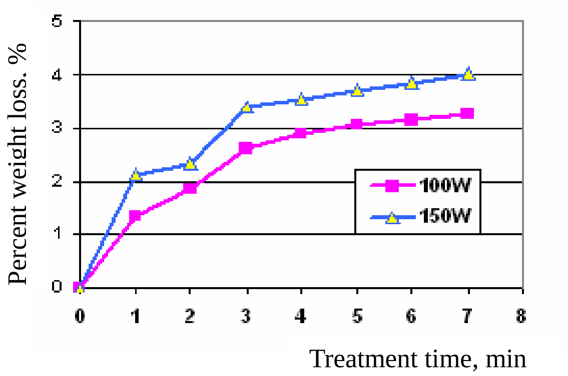


Fig.4. Percent weight loss of Bamboo III vs. plasma treatment time and power

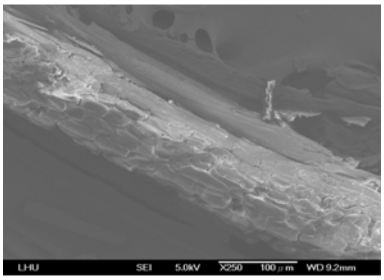
At the power of 100 W, the PWL of Bamboo III (Fig.4) was smaller than that at 150 W (3.30% compared to 3.95% after 7 min treatment, respectively) and increasing treatment time led to the increasing PWL. At 100 W, PWL of single fiber Bamboo IV (Table 2) is smaller than that of the fiber bundle Bamboo III (2.25% compared to 2.95% after 3 min). It can be explained by the higher content of impurity like lignin and amorphous part of Bamboo III, which is more quickly etched than cellulose. The PWL showed the etching, which increases with increasing power and treatment time.

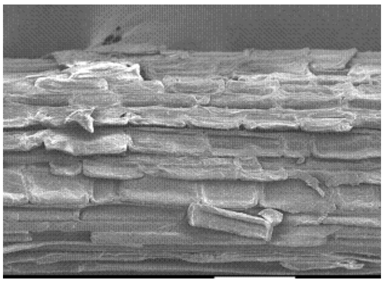
Table 2: Percent weight loss of Bamboo IV depending on plasma treatment time at 100 W

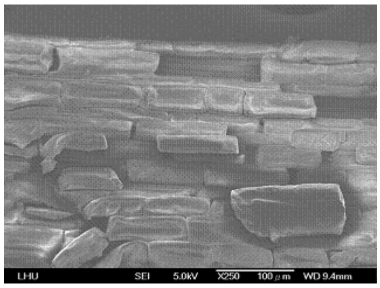
Treatment time	1 min	2 min	3 min	4 min
PWL, %	0.93	1.69	2.25	2.55

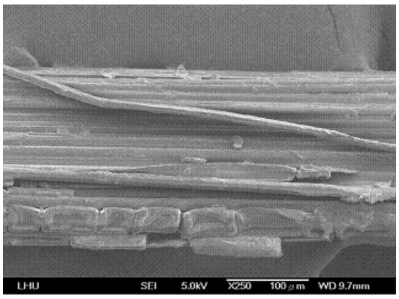
Surface morphology

The SEM imagines of the alkali-untreated Bamboo I with the magnification of 250 and 50 K are shown in the figures 5 and 6.


a) untreated


b) 2 min treated


c) 3 min treated


d) 4 min treated

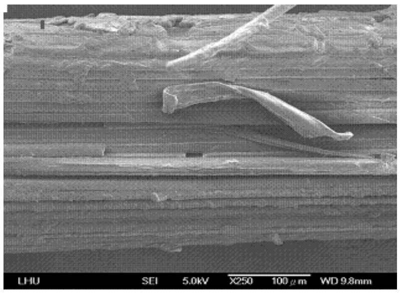
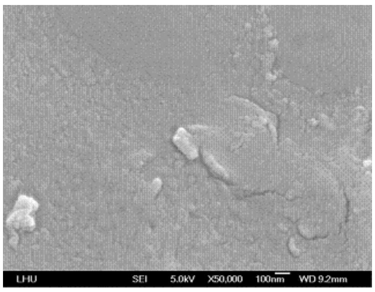
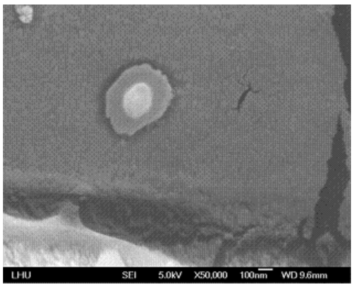
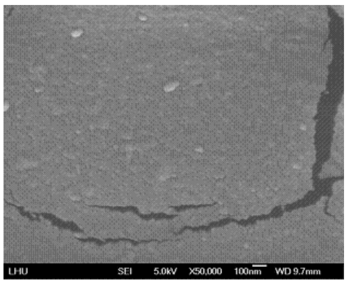

e) 5 min treated

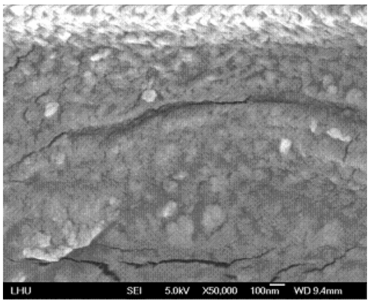
Fig. 5: SEM images of surface morphology of Bamboo I, x250, at treatment power100 W

For the Bamboo I, after extraction by steam explosion, the raw fiber wasn't treated by alkali solution before plasma treatment. It can be seen in Fig. 5a that the protective out- skin of the fiber made of lignin, hemi-cellulose etc. covered fiber. After 2 min plasma treatment, the cracking of the out- skin appeared (Fig.5b). This cracking process developed with the increasing treatment time. At 3 min and 4 min there was the removing of the cracked skin pieces (Fig.5c and 5d), showing the clean surface of the cellulose. After 5 min of treatment, the fiber possesses a clean and regular surface (Fig.5e). Bamboo I is in fact a fiber bundle consisting several micro single fibers (multi-fiber) as shown in Fig.5d and 5e.


a) Un-treated


b) 2 min treated


c) 3 min treated


d) 4 min treated

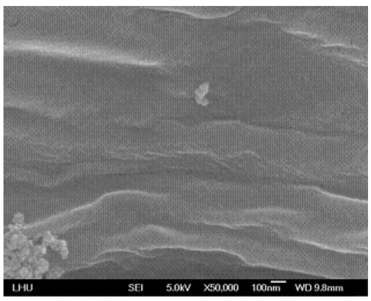
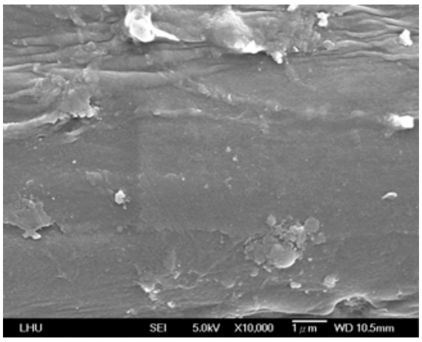
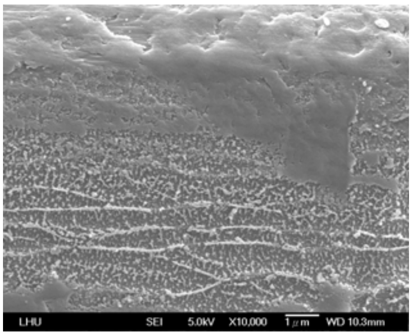

e) 5 min treated

Fig.6: SEM images of Bamboo I surface, x 50K, at treatment power 100 W

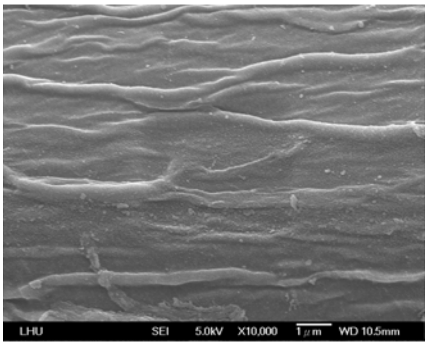
Fig.6 shows that in addition to the cracking process, the atmospheric air plasma treatment also caused the etching and forming the roughness on the fiber surface. Before treatment, the surface wasn't clean and had no significant roughness (Fig 6a). Treatment caused cracking which developed with the time (Fig.6b and 6c). At 3 min there was the appearance of the micro roughness consisting of many pits, spots and flecks (Fig.6d), which also developed with increasing treatment time. At 5 min, SEM imagine showed a clean, regular and rough surface of cellulose with some pieces of impurity with some etched pieces in the bottom left (Fig. 6e). In the case of the alkali-pretreated fiber Bamboo II, since alkali treatment can remove the impurity such as lignin, hemi-cellulose etc., the SEM observation in Fig. 7 shows the etching which caused cleaning and forming the roughness made of pits and spots on the surface, but no significant cracking of the out-skin.



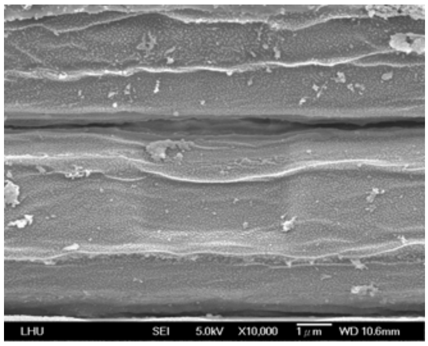
a) Untreated



b) 1 min treated



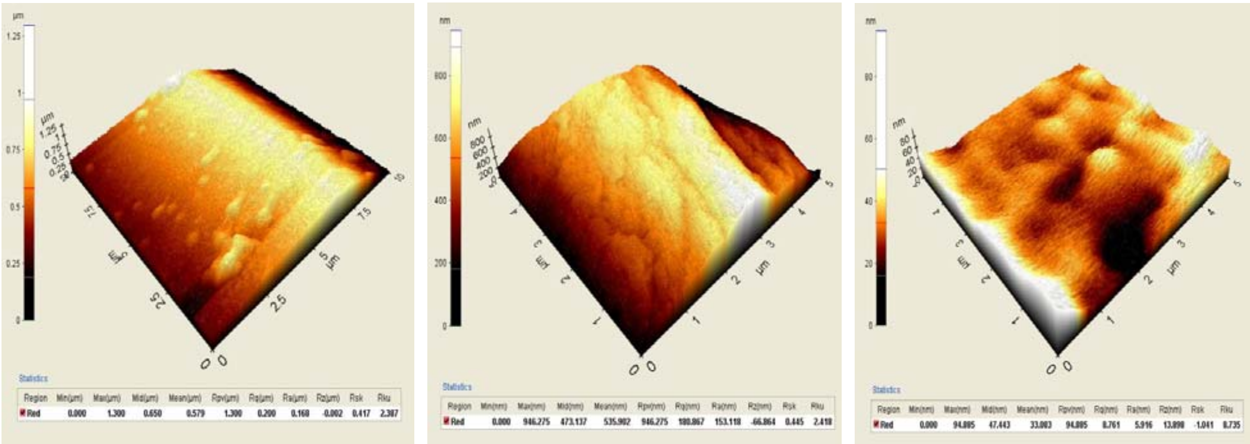
c) 3 min treated



d) 5 min treated

Fig.7: SEM images of Bamboo III surface, x 10K, at treatment power 150 W

For the textile single fiber Bamboo IV, the 3-D atomic force microscopy study of the surface morphology changes due to plasma treatment are shown in Fig. 8. After 1 and 3 min treatment the etching process caused cleaning (Fig.8b) and forming pits and spots (Fig. 8c), which improved the roughness on the treated surface, compared to the unclean and smooth surface of untreated fiber (Fig. 8a). After 3 min treatment, the pits and spots were about 20-30 nm in depth with the average diameter ranging from 200 t0 400 nm.



a) Untreated b) 1 min treated c) 3 min treated

Fig.8: 3-D Atomic force microscopy images of Bamboo IV, treated at 100 W

Dyeability

The dyeing rates of the Bamboo III and Bamboo IV with different plasma treatment time, at the power 100 W, are given in Table 3. The dyeing rate of the bamboo VI increased considerably from 42% (untreated) to 5% after 1 min treatment and reached the maximum (60%) after 3 min, while that of Bamboo III from 32% (untreated) to 50% after 5 min. When the treatment was longer than 3 min the dyeing rate of Bamboo IV decreased. The effect of atmospheric air plasma treatment on Bamboo III is higher than that on textile fiber Bamboo IV, might be due to the higher content of the impurity like lignin and hemi-cellulose of Bamboo III [8, 9]. The maximal value increased 42.8% at Bamboo IV and 56.3% at Bamboo III, respectively, compared with the untreated sample.

Table 3: Effect of plasma treatment time on the dyeing rate of Bamboo III and Bamboo IV

Dyeing rate, %	Bamboo III	Bamboo IV
Un-treated	32	42
1 min treated	-	57
2 min treated	41	59
3 min treated	45	60
4 min treated	49	55
5 min treated	50	

From the results of the morphology study it can be seen that the etching effect of plasma treatment made the surface cleaner and rougher. That led to the higher specific surface area. In addition, air plasma is in fact plasma of a gas mixture, which contains nitrogen and oxygen. Surface might become more hydrophilic due to removing lignin, which is hydrophobic, and due to the modification by oxygen [10]. Higher specific surface area and higher hydrophilicity result in the improvement of wetting ability and absorption ability to dye. The best result for Bamboo IV was obtained at 3 min treatment.

4. CONCLUSION

The surface treatment of different natural bamboo fibers by atmospheric pressure air plasma caused the improvement of tensile strength and modulus of the fibers used for polymer composite as well as the improvement of tenacity of textile bamboo fiber. Percent weight loss, which showed the etching, increased with increasing treatment time and plasma power. The percent weight loss of the textile fiber is smaller than that of fiber used for composite. SEM and AFM observation showed that cracking, pits and forming roughness happened after treatment. Dyeability was remarkably improved after treatment. The effect of treatment is higher at the fiber used for polymer composite.

The obtained results can show that the atmospheric pressure air plasma can be effectively used for treatment of different kinds of bamboo fiber.

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