Influence of needle-punching on strength properties of flax sliver-reinforced composites

Y. Kataoka[1], and K. Goda[2*]

[1]Graduate School of Science and Technology for Innovation, Yamaguchi University, Yamaguchi, Japan
[2]Department of Mechanical Engineering, Yamaguchi University, Yamaguchi, Japan

*Y. Kataoka: i502wc@yamaguchi-u.ac.jp

1. Introduction

Green composites reinforced with natural fibers are expected as an environment-friendly material to be substituted for artificial fiber-reinforced composites such as GFRP (Glass fiber reinforced plastics), because of difficulty of the disposal processing. Natural fibers are finally produced as spun yarns by spinning process from a fiber bundle called the “sliver”, which is obtained through water-retting, dew-retting, scutching, and hackling processes. If the final process is not applied, and the slivers are directly used as a reinforcing form, it is worth saving energy as well as labor. However, the sliver has ‘waviness’ inherent in nature, which largely affects mechanical properties of green composites [1]. Recently a flax sliver without waviness was commercialized, and is expected as a reinforcing material of the composites [2].

The purpose of this study is to broaden the potential of green composites. That is to say, the needle-punching method, one of Z-anchor effects [3], was applied to the flax sliver to investigate how the strength properties are influenced by entanglement of fibers to the out-of-plane direction.

2. Experimental

Uni-directional flax sliver (FLAXTAPE200, LINEO) was used as reinforcement. Epoxy resin (EP-4901, ADEKA Co.) was used as the base material, and mixed with a curing agent (T-403, HUNTSMAN Co.).

In this study, we adopted the needle punch method, which is a kind of non-woven fabric manufacturing method. Needle punch is a technology in which a needle with a minute groove called the “barb” is pierced into a web or a fiber-bundle, and finally fibers are entangled in the thickness direction. This technology exhibits Z-anchor effect. In order to perform needle punch processing, a needle punching machine (produced by Marui Textile Machinery Co.,Ltd.) was used. The number of needle punches (per unit distance) is 50 (0.5/mm), 100 (1/mm), 200 (2/mm), 300 (3/mm), and 400 (4/mm) times. Hereinafter, the abbreviation of the slivers processed as in the above is written as NPM-(number of needle punches). The as-supplied sliver is referred to as UD.

After mixing the base resin and the curing agent, the resin was degassed in a vacuum, and then poured on the flax sliver with or without needle-punching, placed in a Teflon flame. The curing was conducted in a dryer for 24hours at 25°C, and as a post-curing process for 6.5hours at 60°C. The resultant composites were processed in rectangular specimens along or perpendicular to the fiber direction. Both of the sizes were 50mm in length, 11.3-16.0mm in width, and 1.8-3.1mm in thickness.

Tensile test was carried out using an Instron type testing machine (Auto-graph IS-5000, Shimadzu Co.). The cross-head speed was 1 mm/min, and the load and strain were measured until breakage.

3. Results and discussion

Table 1 shows test results of fiber direction. There is a slight variation in volume fraction of fiber (V_f). The tensile strength and Young’s modulus in the table are thus shown in normalized value at V_f=0.15.

Table 1 Tensile properties of UD and NPM specimens along the fiber direction

Sliver form	V_f	Tensile strength [MPa]	Young's modulus [GPa]	Fracture strain [%]
UD	0.187	142	13.5	1.59
NPM-50	0.137	148	11.9	1.58
NPM-100	0.125	144	13.3	1.51
NPM-200	0.114	139	11.0	1.64
NPM-300	0.147	132	10.4	1.55
NPM-400	0.128	127	11.5	1.50

As shown in Table 1, NPM specimens reduced V_f, as compared with UD specimen. In this methodology, each sliver and resin were put into the Teflon mold by hand, without sufficient pressure. It is considered that the reduced volume fraction is affected by the fiber bundle size swelled in the thickness direction during needle-punching process. As a future subject, we need to increase V_f of the specimens by compression molding method. The tensile strength tends to decrease gradually with the increase of the number of needle punches. This is because some fibers oriented in the fiber direction are changed to off-axial direction by needle punching. As compared with UD specimen, NPM-50 and NPM-100 specimens show a slight increase in strength. It is estimated that swelling of the sliver occurs in the thickness direction by needle-punching, and contributes to the improvement of dispersibility of the fibers. To confirm this phenomenon, the cross-sectional observation should be done as a future subject. Regarding the Young's modulus, UD specimen is the highest, whereas that of NPM-200 to 400 specimens decreases.

Table 2 shows the test results of fiber vertical direction. The cause of low V_f is as mentioned above. Although V_f is lower than that of UD specimen, both tensile strength and Young's modulus of NPM specimens are larger than those of UD specimen. It is estimated that such an improvement is attributed to the entangled fiber out of plane.

Table 2 Tensile properties of UD and NPM specimens along the transverse direction to the fiber

Sliver form	V_f	Tensile strength [MPa]	Young's modulus [GPa]	Fracture strain [%]
UD	0.180	17.5	3.53	0.52
NPM-50	0.123	21.2	3.94	0.76
NPM-100	0.150	17.6	3.90	0.57
NPM-200	0.136	22.1	3.88	0.71
NPM-300	0.130	21.1	3.85	0.69
NPM-400	0.111	25.6	3.79	0.85

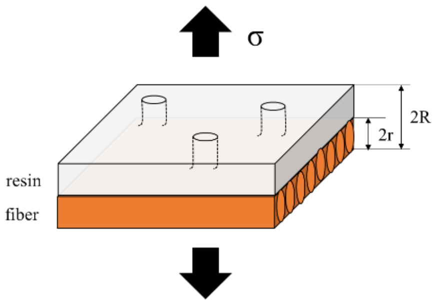

Fig.1 Schematic of a proposed model

In order to investigate the influence of V_f on the strength in the fiber vertical direction, an interfacial strength model was proposed. This model is made by adding Z-directional fiber arrangement to a resin layer, as shown in Fig.1 [4]. That is, some fibers flow from the fiber layer to resin layer along the out-of-plane direction, whereas the resin flows from the resin layer to the outflow portion of the fibers. Therefore, this composite is a pair of fiber volume fraction of fiber inflow ratio ω_f and remaining fiber volume fraction $(1-\omega_f)$, which is recognized as a unit. And the whole composite is expressed by stacking the units. In this study, we investigated ω_f experimentally under each condition. From this model, Young's modulus E_c of the composite to the fiber vertical direction can be obtained based on Reuss law [5] as in the below.

$$E_c = \frac{E_f{}^c E_m{}^c}{v_f E_m{}^c + (1-v_f)E_f{}^c} \quad (1)$$

The superscript c means that E_f and E_m are changed to E_f^c and E_m^c, respectively, by Z-directional fiber arrangement. Assuming that the fracture along the fiber vertical direction is determined by the fiber-resin interfacial strength σ_{mu}^c, it can be estimated from Eq.(1) and the tensile strength of σ_c^* fiber vertical direction as follows:

$$\sigma_{mu}^c = \frac{\sigma_c{}^*\{v_f E_m{}^c + (1-v_f)E_f{}^c\}}{E_f^c\left\{1-\frac{r}{R}\left(1-\frac{E_m{}^c}{E_f{}^c}\right)\right\}} \quad (2)$$

where, R is a distance between fibers, and r is the fiber radius. By assuming a square array and a hexagonal array of the fibers, σ_{mu}^c was calculated. The relationship between the interfacial strength and the number of needle punches is shown in Fig.2.

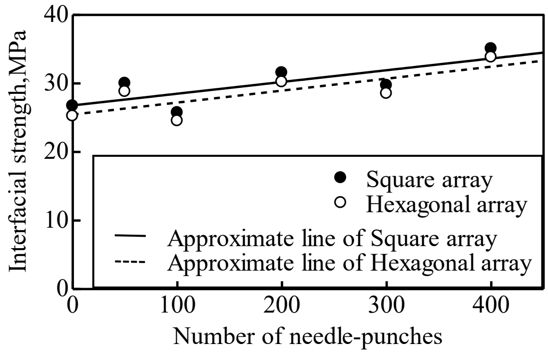

Fig.2 Interfacial strength vs. number of needle-punches

The interfacial strength tends to increase gradually in both square and hexagonal arrays as the number of needle punches increases. It is considered that the needle punching process enhanced resistance in the tensile direction due to the entanglement in the fiber vertical direction of the sliver. In particular, in NPM-400, the interfacial strength increased by 30% or more compared to UD. Such a result verifies a positive effect of the needle punch processing.

References

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