STRAIN RATE DEPENDENCE ON TENSILE PROPERTIES FOR BAMBOO FIBER THERMOPLASTIC POLYMER COMPOSITES

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Keywords: Natural fiber, Strain rate, Stress-strain relation, Formulation.

Abstract

In this study, the strain rate dependence on the mechanical properties of bamboo/polypropylene (PP) composites with various fiber weight contents molded by the injection molding was investigated. For this purpose, the strain rate dependence on the tensile strength of single bamboo fibers was firstly measured and that on the strength of composites was also investigated, then the effect of interface between bamboo fibers and matrix on the strain rate dependence was estimated. Finally, the visco-elasticity and visco-plasticity as well as the plastic strain hardening on the stress-strain relations of the composites were estimated using the modified G'Sell-Jonas phenomenological model. Consequently, it was found that the strain rate dependence of bamboo fibers and PP matrix were almost same and it was presumed that the interface between the fibers and matrix was insensible to the strain rate.

1. Introduction

Bamboo is a quite valuable resource deeply related with our Japanese lives since ancient times, in terms of life instruments such as the baskets and sieves, the architectural uses such as fixtures and finish materials of Japanese wooden houses. In these days, however, bamboo was limited to extremely less application because of many practical uses of glass fiber reinforced plastics (GFRP), as well as synthetic resins such as phenol, polyethylene, polypropylene and poly-carbonate. Recently, in addition, the rapid growth of bamboo roots brings problems of breaking the building bases, water-supplies and drain pipes. Thus, it is said that the bamboo industry of Yamaguchi prefecture in Japan is considering a discard method of bamboo without any use of high performance inherent in bamboo.

Now, some automotive companies make an attempt to apply the bamboo fibers as reinforcements into the interior parts using the injection molding. Plastic materials are increasingly used for construction purposes in such automotive engineering and the aerospace industry, where high strain rates up to $300s^{-1}$ can be realized. It is well known that the strain rate dependence on the mechanical properties of polymer materials is larger than that of metals because plastic materials have a strong visco-elastic behavior. The characterization of the mechanical properties at high speeds and high strain rates becomes more and more important, being a major consideration in appropriate material data for the performance of FEM crash simulations.

In this study, the strain rate dependence on the mechanical properties of bamboo/polypropylene (PP) composites with various fiber weight contents molded by the injection molding was investigated. For this purpose, the strain rate dependence on the tensile strength of single bamboo fibers was firstly measured and that on the strength of composites was also investigated, then the effect of interface between bamboo fibers and matrix on the strain rate dependence was estimated. Finally, the visco-elasticity and visco-plasticity as well as the plastic strain hardening on the stress-strain relations of bamboo/PP composites were estimated using the modified G'Sell-Jonas phenomenological model.

2. Experimental method

2.1 Single bamboo fiber tensile tests

Single bamboo fibers made from a "Moso" bamboo in Shimane prefecture of Japan was prepared in this study. The bamboo was crushed to pieces by the carding machine (Fiberlizer, West technology development). The obtained bamboo fibers were classified using the sieve of 381μm and 106μm. The average size of bamboo fibers is shown in Table 1.

Table 1 Average size of bamboo fibers

Sieve mesh size[μm]	Length[mm]	Width[mm]	Aspect ratio
381	1.15	0.31	3.59
381-106	2.77	0.30	9.62

The gauge length of single fiber tensile specimen was 3mm. The tests were carried out at room temperature, and the tensile speed were 10^0, 10^1, 10^2, 10^3[mm/min]. These tensile speeds were comparable to the strain rate of 5.56×10^{-3}, 5.56×10-^{2}, 5.56×10^{-1} and 5.56×10^0, respectively. The load was obtained from the load cell and the strain was calculated from the crosshead speed ant times. The number of specimen was 15 on each condition.

2.2 Bamboo fiber/PP composites

2.2.1 Effect of bamboo fiber contents

No classification bamboo fibers were used here, the polypropylene of H100M (Prime Polmer Co., Ltd. Japan) was used as matrix. In order to improve the interfacial adhesion of bamboo fiber and matrix, a maleic anhydride-grafted polypropylene (MA-PP, Kayaku Akzo Co. Ltd. Japan) was used as a coupling agent. The rate of MA-PP for the resin was 2wt% against the PP weight. Before molding, to remove the extra moisture in bamboo fibers the bamboo fibers were fully dried in a constant temperature chamber (MOV-112F, Sanyo Electric Co., Ltd. Japan). The pellets including the fibers, PP and MA-PP were prepared using a single screw extruder (MUSASHINO KIKAI Co. Japan) The dumbbell-shaped test specimens were prepared using a injection molding machine (Bevel 20, Shinko Sellbic Co. Ltd. Japan) under conditions of molding temperature of 190 [^{o}C] and injection pressure of 5MPa. The dimensions of specimens were 18mm in length, 3mm in width and 2mm in thickness. The contents of bamboo fibers were 0, 1, 2, 5, 10 and 20wt%. The tensile tests were carried out at room temperature with the tensile speeds of 10^0, 10^1, 10^2 and 10^3 [mm/min]. These tensile speeds were comparable to the strain rate of 9.26×10^{-4}, 9.26×10^{-3}, 9.26×10^{-2} and 9.26×10^{-1}, respectively. The load was obtained from the load cell and the strain was calculated from the crosshead speed ant times. The number of specimen was 3 on each condition.

2.2.2 Effect of aspect ratio

In order to investigate the influence of bamboo fiber aspect ratio on the mechanical properties, the classification of fibers was done using a sieve of 355μm and 500μm. The fiber dimensions were denoted in table 2.

Table 2 Fiber dimensions after classification

Sieve mesh size[μm]	Length[mm]	Width[mm]	Aspect ratio
500	0.99	0.50	2.19
355	0.59	0.39	1.56

The polypropylene of 900GP (Prime Polmer Co., Ltd. Japan) was used as matrix. The coupling agent of MAPP was also used here. The content of bamboo fibers was 5wt%. The molding method and test conditions were equally above tests.

2.2.3 To obtain the true stress-true strain curves

In-situ observation for the tensile test was carried out using a high speed camera (FASTCAM-1042PCI, Photoron Co. Ltd. Japan) in order to obtain the transformation of the specimen shapes. From the measurements of specimen width the cross-section of specimens was approximately estimated, the true strain was obtained using following equation [1].

$$\varepsilon_{true} = \int_{l_0}^{l} \frac{1}{l} dl = \ln\left(\frac{l}{l_0}\right) = \ln\left(\frac{A_0}{A}\right) \tag{1}$$

3. Experimental result

3.1 Single bamboo fiber tensile tests

The obtained tensile properties were shown in Table 3. The average values were denoted in this table. The strain rate dependency on the tensile strength was cleared.

Table 3 Effect of strain rate on tensile properties of bamboo fibers

Strain rate [1/s]	Tensile strength [MPa]	Fracture strain [%]	Young's modulus [GPa]
5.56×10^{-3}	284.5	8.85	4.11
5.56×10^{-2}	360.2	5.71	6.00
5.56×10^{-1}	366.8	5.30	6.15
5.56×10^{0}	434.2	9.72	4.75

3.2 Bamboo fiber/PP composites tensile test

3.2.1 Effect of bamboo fiber contents on tensile properties

The effect of bamboo fiber contents on tensile strength for bamboo fiber/PP composites was shown in Table 4. The relation to between tensile strength and fiber content was shown in Figure 1. From this figure the strain rate dependence on the tensile strength for the composites was confirmed. The critical fiber content to improve the tensile strength was 5 wt% in this study. The reason why the tensile strength doesn't increase more than the content of 5 wt% was the insufficient commixture between fibers and resin using presented method.

The relations between the normalized maximum stress (tensile strength) divided by the maximum stress at the lowest strain rate and the strain rate were shown in Figure 2 using the semi-logarithmic notation. It was found that these relations followed the linear lines. The dependence of strain rate on the tensile strength was quantitatively defined using the slope of these lines in this study. These slopes Δ were shown in Figure 3. It was cleared from this figure that the strain rate dependence decreases as increase of the bamboo contents. It was suggested that the strain rate dependence of interface between the fibers and matrix was low because the total amount of interface area increases as increase of the bamboo contents. To decrease the total amount of interface area, it was essential that the aspect ratio of fibers increases.

Table 4 Effect of bamboo fiber contents on tensile strength for bamboo fiber/PP composites

Strain rate [1/s]	Tensile strength [MPa]					
	0wt%	1wt%	2wt%	5wt%	10wt%	20wt%
9.26×10^{-4}	35.6	39.0	38.7	47.5	47.3	46.1
9.26×10^{-3}	40.4	44.7	45.0	50.7	52.1	51.3
9.26×10^{-2}	45.1	53.6	51.1	58.4	57.6	53.7
9.26×10^{-1}	49.0	59.6	55.9	63.0	63.1	60.7

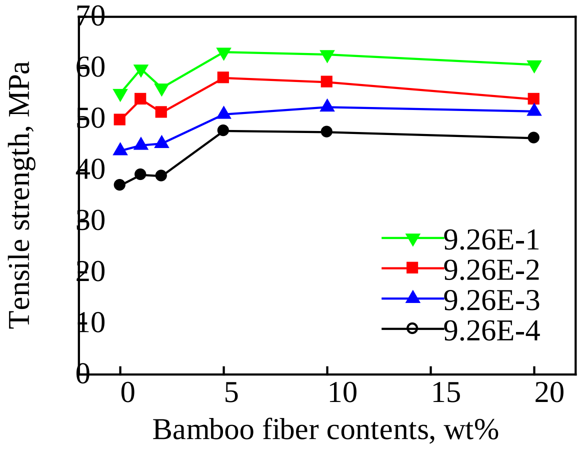


Figure 1. The relation between the tensile strength and fiber contents for bamboo fiber / PP composites.

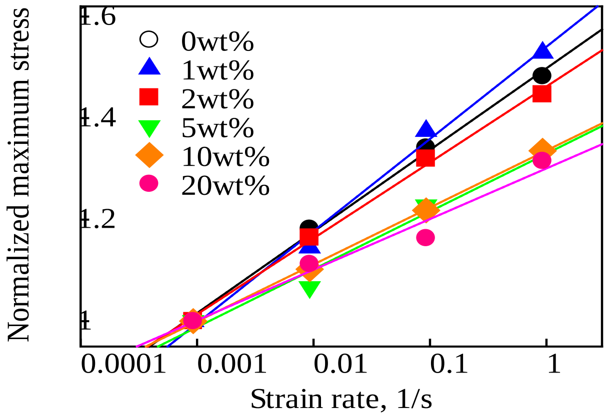


Figure 2. The relation between the normalized maximum stress and strain rates for bamboo fiber / PP composites.

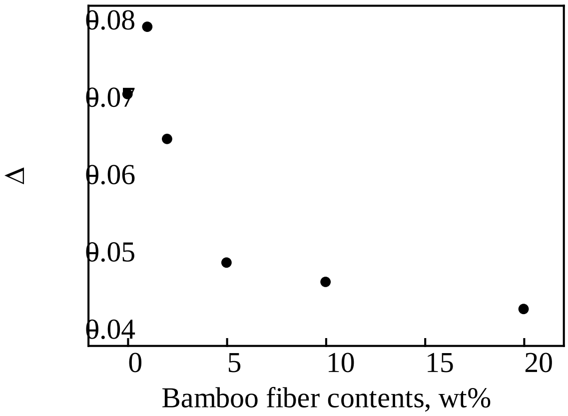


Figure 3. The relation between the slope Δ and bamboo contents for bamboo fiber / PP composites.

3.2.2 Effect of aspect ratio on tensile properties for bamboo fiber/PP composites

The effect of fiber aspect ratio on tensile properties for bamboo fiber/PP composites is shown in Table 5. The relations between the normalized maximum stress and the strain rate were shown in Figure 4 using the semi-logarithmic notation. From this figure the dependence of strain rate on the tensile strength increases as increase of the fiber aspect ratio. It was derived from the decrease of interface.

Table 5 Effect of fiber aspect ratio on tensile strength : aspect ratio A of 1.56 and aspect ratio B of 2.19.

Strain rate [1/s]	Tensile strength [MPa]		Fracture strain [%]		Young's modulus [GPa]	
	A	B	A	B	A	B
9.26×10^{-4}	45.3	46.7	90.7	47.5	1.19	1.06
9.26×10^{-3}	46.1	47.9	79.8	25.5	1.18	1.13
9.26×10^{-2}	53.6	57.3	16.8	14.3	1.30	1.43
9.26×10^{-1}	57.1	61.8	10.2	10.3	1.37	1.43

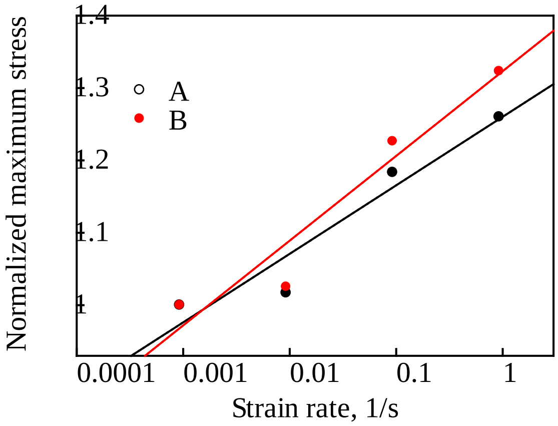
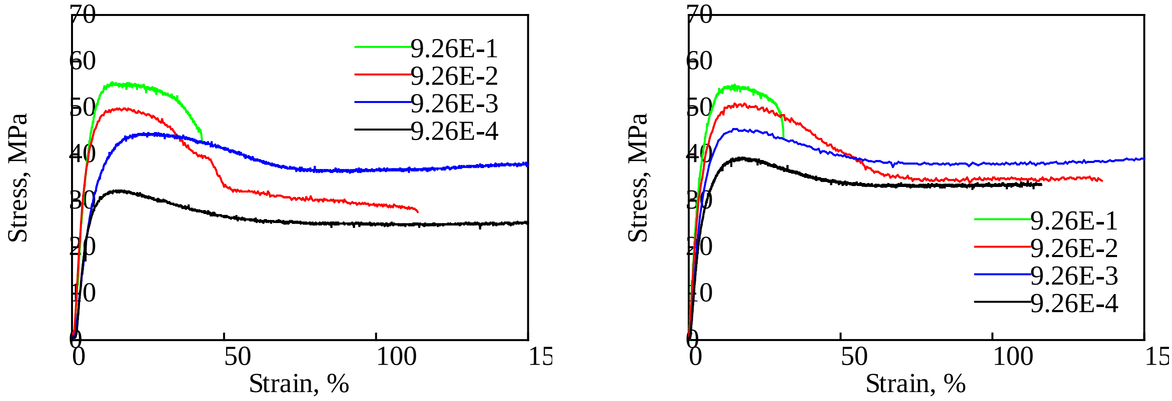


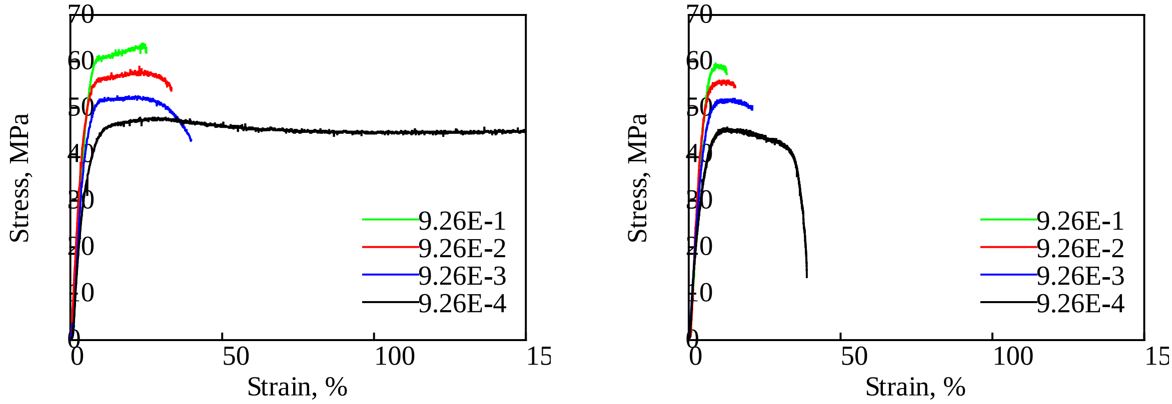
Figure 4. The effect of fiber aspect ratio on the relation between the normalized maximum stress and the strain ratio.

3.2.3 Stress-strain curves

The representative nominal stress-strain curves for neat PP, 2, 5 and 20 wt% bamboo/PP composites were shown in Figure 5 (a)~(d), respectively. It was shown that the nonlinear behaviors before maximum stress and the stress reduction due to a necking occurred. The plateau stress also depended on the strain rates. The comparison between the nominal and true stress-strain curves were denoted in Figure 6 for 5wt% bamboo/PP composites. At the strain rate of 9.26x10^{-3}, the necking behavior was observed and the stress increase due to strain hardening occurred in the true stress-strain curve. In the case of the strain rate of 9.26x10^{-1}, the failure mode was approximately brittle and the shape change of specimen was barely observed.

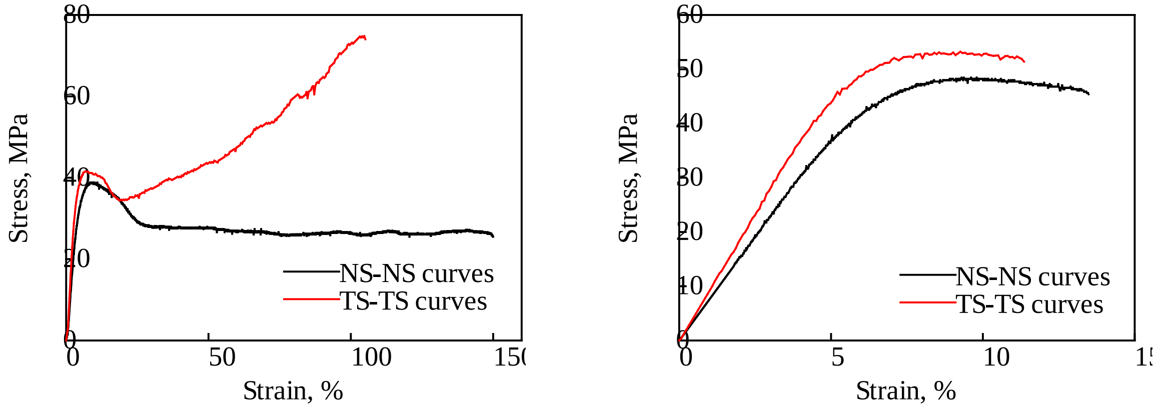


(a) neat PP (b) 2 wt%-bamboo/PP composites



(c) 5 wt%-bamboo/PP composites (d) 20 wt%-bamboo/PP composites

Figure 5 Stress-strain curves



(a) 10 mm/min (9.26x10^{-3} strain rate) (a) 1000 mm/min (9.26x10^{-1} strain rate)

Figure 6 The comparison between the nominal and true stress-strain curves for 5wt% bamboo/PP composites

4. Discussion

4.1 Application of the G'Sell-Jonas model

For semi-crystalline polymers, the phenomenological G'Sell-Jonas model is frequently used [1-3]. This model describes the dependence of the flow curve on the strain rate, strain and temperature using following equation.

$$\sigma(\dot{\varepsilon},\varepsilon,T)=K\cdot(\dot{\varepsilon})^m\cdot\exp\left(h\varepsilon^2\right)\cdot\{1-\exp(-W\varepsilon)\}\cdot\exp\left(\frac{a}{T}\right) \tag{2}$$

Here, σ and ε is the true stress and true strain, T is the absolute temperature and K, a, W, h and m are material constants, respectively. This model comprises the viscoelasticity $\{1-\exp(-W\varepsilon)\}$ and the visco-plasticity $(\dot{\varepsilon})^m$ as well as the plastic strain hardening $\exp\left(h\varepsilon^2\right)$ and the effect of temperature $\exp\left(\frac{a}{T}\right)$. The application result was shown in Figure 7. From this figure it was found that the strain hardening behavior after necking was agree with experimental results, however the stress rapid reduction after yielding due to necking was not agree with ones.

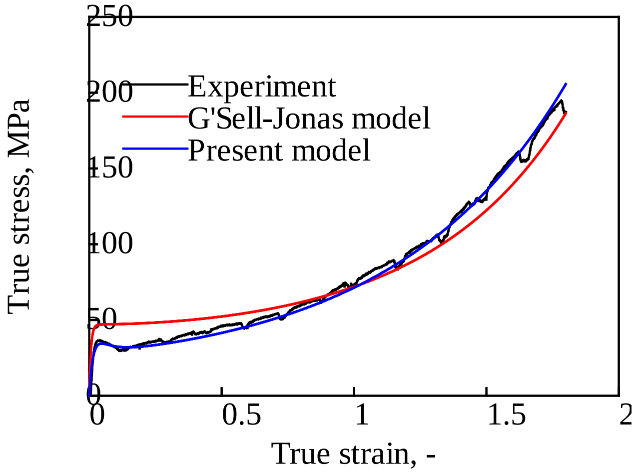


Figure 7. The estimation results of the true stress-true strain curve using the G'Sell-Jonas model and present model for 5wt% bamboo/PP composites at the 9.26x10^{-3} strain rate.

4.2 Modification of the G'Sell-Jonas model

We proposed the modified G'Sell-Jonas model in order to consider the necking behavior by following equation in this study.

$$\sigma(\dot{\varepsilon},\varepsilon,T)=K\cdot(\dot{\varepsilon})^m\cdot\exp\left(h\varepsilon^n\right)\cdot\{1-\exp(-W\varepsilon)\}\cdot\exp\left(\frac{a}{T}\right)\cdot\{1+\alpha\exp(-\beta\varepsilon)\} \tag{3}$$

Here, α and β are material constants, and the regression parameters in equation 3 were denoted in Table 6. The estimation results of the true stress-true strain curve was also shown in Figure 7. The stress rapid reduction after yielding due to necking was well agree with the experimental results as well as the strain hardening behavior after necking.

Table 6 Regression parameters for the calculation according modified G'Sell-Jonas model

Strain rate [1/s]	h	W	K	n	α	β	m	a	T
9.26×10^{-4}	0.81	42.1	11.3	1.36	1.39	40.3	0.0375	400	295
9.26×10^{-3}	-1.78	25.1	11.2	1.19	1.55	13.7			
9.26×10^{-2}	-3.03	18.4	14.4	0.92	1.23	9.72			
9.26×10^{-1}	-8.75	15.1	14.3	1.54	1.24	6.46			

5. Conclusions

In this study, the strain rate dependence on the mechanical properties of bamboo/polypropylene (PP) composites with various fiber weight contents molded by the injection molding was investigated. For this purpose, the strain rate dependence on the tensile strength of single bamboo fibers was firstly measured and that on the strength of composites was also investigated, then the effect of interface between bamboo fibers and matrix on the strain rate dependence was estimated. Finally, the visco-elasticity and visco-plasticity as well as the plastic strain hardening on the stress-strain relations of bamboo/PP composites were estimated using the modified G'Sell-Jonas phenomenological model. Consequently, it was found that the strain rate dependence of bamboo fibers and PP matrix were almost same and it was presumed that the interface between the fibers and matrix was insensible to the strain rate. The strain rate dependence on the mechanical properties for bamboo/PP composites was high and the contribution of the visco-elasticity of matrix was quantitatively predicted using the phenomenological model.

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