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Fiber alignment and property direction dependency of FRC extrudate

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Abstract

This paper studies the phenomenon of fiber alignment during the extrusion process. The fiber alignment is largely dependent on shapes of dies and the compression as well as the shear force generated in the extruder. The fiber alignment orientation, of course, would lead to direction dependency of the tensile properties of fiber-reinforced cement (FRC) extrudates. Such a dependency has been investigated in present study. It is found that when fiber volume ratio is small, say 1% of the glass fiber, the majority of the fiber can be aligned in the extrusion direction. As a result, the tensile strength of the thin plate along the extrusion direction is much higher than that along the transverse direction. When the total fiber volume ratio is increased to 2% or 4%, the fiber volume along the transverse direction is largely increased although the percentage of the fiber aligned along the extrusion direction is still higher. Thus, the tensile strength at a transverse direction can be significantly enhanced. In fact, the tensile strength of the samples along the transverse direction is almost the same as that along the extrusion direction when the fiber volume ratio reaches 2%. Furthermore, the strength of the sample at the extrusion direction does not increase proportionally to the fiber volume ratio. For the comparison purpose, plain sheets without any fibers have been prepared by both casting and extrusion. Mechanical properties of the sheets have also been tested and the test results show that extrusion process and fiber addition do have effects on enhancing the tensile properties. Polymer coating on the surface of the samples has also been used to improve the tensile properties of the extrudates with low fiber volume ratio, which shows some promising results.

Keywords: Extrusion technique; Tension; Fiber distribution; Fiber-reinforced composite; Cement

1. Introduction

The inherent tensile strength and toughness of cement-based matrix can be significantly enhanced by adding the appropriate type and amount of fibers [1–8]. It is also well known that the alignment orientation of fibers within a matrix has direct effects on enhancing the strength and toughness of fiber-reinforced cement (FRC)-based composites. Generally speaking, the short fiber distribution within a matrix is random when the samples are fabricated by traditional methods such as casting [2–4]. The properties of such materials can be considered as isotropic. However, the fibers within a matrix can be aligned into the desired direction when the samples are fabricated by extrusion technique through high compression and high shear [5–9]. In general, a large amount of fibers are aligned in parallel along the extrusion direction, and only a small portion of fibers may be distributed in the transverse direction. The properties of thin plates manufactured by extrusion in two directions, parallel and transverse, may be different, which means the plates show anisotropic properties. The fiber alignment orientation ratio of the extrusion direction to other directions is affected mainly by the materials, mixing proportion, cohesion of the matrix, feature of pressure head and die geometry, fiber type and length, aspect ratio and the fiber volume ratio. When other conditions are fixed, a lower fiber volume ratio would lead to a higher fiber alignment orientation ratio, i.e. more fibers would be aligned in the extrusion direction due to less viscosity of the extrudate. There are some theoretical models that can be used to describe the cementitious flow and fiber distribution in an extruder [6,10,11].

It is not always necessary for the fibers to be distributed in a unified direction, especially for thin sheets acting like a two-way slab. The fiber distribution at two directions can provide a similar bidirectional tensile strength and tough-

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ness. The tensile strength and toughness of the extrudate products are indexes of their resistance to direct longitudinal tensions and suddenly applied transverse loads, respectively. For roofs, wall products and other plate structures, the tensile strength and toughness could be considered as indexes of the resistance to the nailing, cutting and bending.

Though the tensile strength and toughness of a cementitious product may be improved by adding fibers in the composition, the use of fibers has certain drawbacks in some cases, such as increase in the difficulty in mixing and extrusion process. As the amount or length of fiber increased, the processability of the material is reduced. Moreover, a small fiber volume ratio has very limited effects on improving the tensile strength and toughness of the extruded products, especially the transverse direction properties. But superfluous use of fibers not only increases the process difficulty, but also the cost. Moreover, it is testified through experiments that when fiber volume ratio exceeds a certain amount, the fibers cannot be efficiently utilized to enhance the tensile strength and toughness of the products. The amount at which fiber properties can be fully used is named as the saturated point by the authors. Obviously, the saturated point for toughness may be different from that for tensile strength.

This paper studies the direct tensile properties of the cementitious thin plates reinforced with discontinuous glass fibers at parallel and transverse directions manufactured by extrusion technology. The specimens were fabricated by extrusion with different fiber volume ratios, at 0%, 1%, 2% and 4%, respectively. In addition, in order to figure out the influence of different processing methods, casting and extrusion, on the tensile behaviour of the cementitious products, one group of specimens was cast without additional fibers. The specimens were tested and the results were compared with the extrudates having the same mixing proportions. The fiber distribution within a matrix fabricated by extrusion was investigated using an optical microscope. The critical fiber value to guarantee similar tensile properties in two directions was discussed based on experimental observation. Furthermore, to improve the tensile properties of the products with lower fiber volume ratio, polymer coating on the surface of the specimens was used. It was found that the polymer coating could increase the tensile strength of the specimens at a transverse direction.

2. Experiment

2.1. Specimen preparation

The basic materials used in this investigation were: (i) short alkali-resistant glass fibers (see Table 1); (ii) Type I Portland cement with a specific gravity of 3.15 and a fineness of 385 m^2/kg; (iii) two types of silica sand, 600–300 and 150–90 μm in nominal diameter, from David Ball, as inert fillers to improve the finish of the extrudates; (iv) ground blast-furnace slag (see Table 2). In addition, superplasticizers and rheological enhancing polymers were used to improve the workability and extrudability of the mixture. Epoxy and polyester were used for surface coating.

Table 1
Properties of the short glass fibers

Density (g/cm^3)	Tensile strength (MPa)	Elastic modulus (GPa)	Length (mm)	Diameter (μm)	Aspect ratio
2.53	3600	70	12	8	1500

The mix proportions are listed in Table 3. Four batches were prepared. Batch #1 was plain cement composite, fabricated by either casting or extrusion. Batch #2, Batch #3 and Batch #4 were glass fiber-reinforced cement (GFRC) extrudates with fiber volume ratio of 1%, 2% and 4%, respectively. The effect of extrusion technique on improving the strength and toughness of extrudates can be found when comparing the results of specimens prepared by different methods, either casting or extrusion, with the same mix proportion (#1). While comparing the results of specimens of Batch #2, #3 and #4 with those of specimens of Batch #1 fabricated by extrusion, the effect of fiber volume ratio on enhancing the strength and toughness of extrusion products can be investigated.

The cement, slag, water and superplasticizer were mixed first for 3 min in an electric paddle mixer. To fabricate the specimens by casting, the mixed material was pressed into the metal mould and compressed to the desired size of $250 \times 75 \times 6$ mm. The free surface (one 75×6 mm face) was smoothed using a scraper. The specimens were demoulded after keeping in the moulds for 24 h and then cured with the extrudates in a KOTA Isothermal Testing System Chamber. For extrusion products, to disperse the short fibers uniformly and improve the interfacial zone between matrices and fibers, cementitious slurry, made of slag, cement, water and superplasticizer, was prepared first. When this cementitious slurry was ready, the short fibers were added to the slurry and mixed for about 3 min. Then all the other components, which had been premixed for 3 min in advance, were added together followed by 3 min of mixing. Finally, mixed dough-like fresh cementitious composites were then fed into the pugmill chamber of a single screw vacuum extruder. After further mixing, de-airing and compacting in the extruder, the composites were pushed out through a sheet die with a cross-sectional area of 300×6 mm. The extrudates were cured under a plastic cover for 24 h, then, these extrudates were placed in a KOTA Isothermal Testing System Chamber (SSE-28CI-A) for a 28-day equivalent low-pressure steam curing as introduced by the ACI Recommended Practice 517.

2.2. Tensile strength test

After curing, the specimens were cut into $250 \times 75 \times 6$ mm plates in parallel and transverse directions relative to the

Table 2
Chemical compositions of slag (%)

SiO_2	Al_2O_3	Fe_2O_3	TiO_2	K_2O	Na_2O	CaO	MgO	LOI	SO_3
28.48	12.56	1.56	0.44	0.44	0.20	39.50	7.40	0.50	8.48

extrusion direction for direct tension. Three specimens in the parallel direction and three in the transverse direction for each batch of extrudates were tested. Some other specimens were coated with polymer. For tensile test, each end of a specimen was glued to two aluminum plates that were fixed to loading fixtures through pins. The loading fixtures were then connected to MTS hydraulic grips. On each side of the specimen, a linear variable differential transformer (LVDT) was attached to measure the deformation of the specimen (Fig. 1). These two LVDTs were connected to the digital controller of the MTS machine through two AC conditioners. The average output of these two LVDTs was used as a feedback signal to form a closed-loop control. Considering that cracks may occur at the boundary of the aluminum plate and the test portion of the specimen, the span of the LVDT was slightly extended beyond the boundary. To ensure proper alignment of the LVDT and friction-free movement of the electric core in the LVDT, preload checking was performed. The uniaxial tension tests were conducted at a displacement rate of 0.003 mm/min. The data of load and deformation were recorded directly through Test Ware-SX into the computer.

2.3. Fibers distribution

To examine the fiber distribution within the GFRC extrusion products, six samples from each batch with 1%, 2% and 4% glass fiber volume ratio, respectively, were prepared. Each sample had a 1 cm^2 area being polished in advance. The fiber distribution was then investigated using a polarizing optical microscope (Olympus BH-2, Japan).

2.4. Polymer coating

The mechanical properties of cementitious composites, such as tensile strengths and toughness, can be improved by polymer coating. Such study was also conducted through direct tensile testing of the coated extrudates. The polymer used in this study was Epikoto 815 and polyester 8200. The epoxy resin and polyester were mixed with hardener at a ratio of 10:1 and 100:3.7, respectively. The specimens were desiccated in vacuum for 24 h before coating. Then, the specimens were dipped in polymer liquid for 15 min and hardened in air for another 24 h.

Table 3
Mix proportions

	Cement	Slag	SS1	SS2	GF (%)	FDN	W/B
Batch #1	0.5	0.5	0.20	0.13	0	0.01	0.28
Batch #2	0.5	0.5	0.20	0.13	1	0.01	0.28
Batch #3	0.5	0.5	0.20	0.13	2	0.01	0.28
Batch #4	0.5	0.5	0.20	0.13	4	0.01	0.28

SS1 and SS2: 600–300 and 150–90 μm silica sand, respectively; GF: glass fiber volume ratio; B: binder (cement + slag); W: water; FDN: superplasticizer.

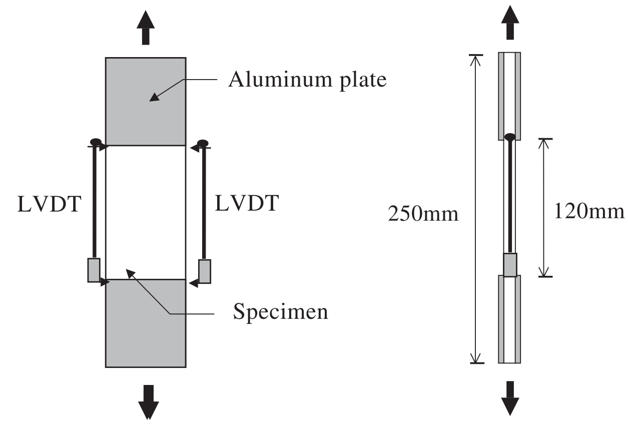

Fig. 1. Setup of the direct tensile test.

3. Test results and discussion

In Fig. 2, Curve 1 shows a typical tensile stress and strain curve of Batch #1 specimen fabricated by casting. The average tensile strength (Table 4) only reached 2.27 MPa. It was low compared with the results of specimens fabricated by extrusion (Curves 2 and 3). The average strength of extruded specimens in the parallel and transverse directions reached 6.20 and 5.36 MPa, respectively. Therefore, it is verified that the extrusion process can improve the tension strength of a matrix. The ratio of the average transverse strength to average parallel strength for plain matrix manufactured by extrusion is about 0.86. The velocity profile and the shear force distribution in pressure head and rotation of the extruder may cause the slight difference in strengths between the transverse and parallel directions. Fig. 2 also

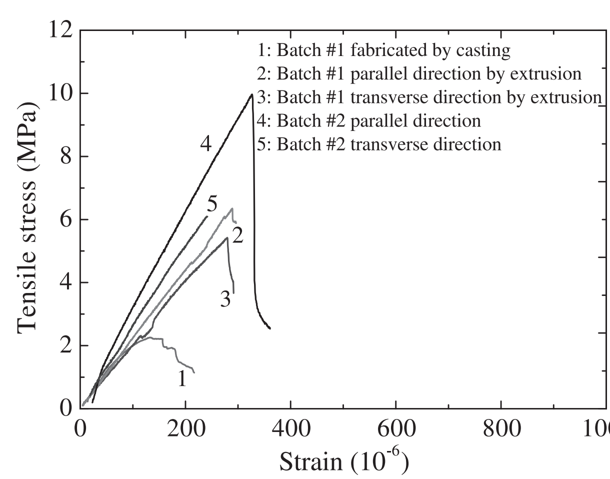

Fig. 2. The tensile stress and strain curves of Batch #1 by casting and by extrusion and Batch #2 with 1% fiber dosage.

Table 4
Test result summary

	Parallel direction				Transverse direction			
	Before coating polymer		After coating polymer		Before coating polymer		After coating polymer	
	Peak strength (MPa)	Peak strain (10^{-6} mm/mm)	Peak strength (MPa)	Peak strain (10^{-6} mm/mm)	Peak strength (MPa)	Peak strain (10^{-6} mm/mm)	Peak strength (MPa)	Peak strain (10^{-6} mm/mm)
Batch #1[a]	1.94	127	–	–	–	–	–	–
	2.25	133	–	–	–	–	–	–
	2.61	146	–	–	–	–	–	–
Average	2.27	135	–	–	–	–	–	–
Batch #1	4.88	276	–	–	5.39	278	–	–
	7.40	288	–	–	5.69	280	–	–
	6.33	289	–	–	5.01	282	–	–
Average	6.20	284	–	–	5.36	280	–	–
Batch #2	9.98	329	10.35	572	5.58	208	10.54	457
	12.15	438	11.88	506	7.53	284	10.23	432
	9.52	349	12.92	573	6.09	241	8.69	405
Average	10.55	372	11.72	550	6.40	244	9.82	431
Batch #3	10.28	338	9.91	393	10.19	386	10.78	387
	10.57	396	11.41	382	10.86	416	9.83	417
	10.95	369	12.87	516	10.61	405	10.89	439
Average	10.60	368	11.40	430	10.55	402	10.50	414
Batch #4	11.46	481	–	–	11.67	501	–	–
	11.97	448	–	–	10.27	476	–	–
	11.07	512	–	–	12.26	517	–	–
Average	11.50	480	–	–	11.40	498	–	–

[a] Batch #1 fabricated by casting without fibers, and the parallel direction means the direction along the 250-mm-length side of the specimen by casting.

shows the results of tension stress and strain curve for the extrudate of Batch #2 with 1% fiber volume ratio. The average strength in the parallel and transverse directions equals 10.55 and 6.40 MPa, respectively. The average parallel strength of a specimen with 1% fiber volume ratio is about 70% higher that of a plain matrix. But the average transverse strength increased by only 19% correspondingly. The ratio of average transverse to average parallel strength for Batch #2 decreased to 0.61. It is suggested that most fibers be aligned in the extrusion direction with only a small portion of fibers distributed in the transverse direction. To verify this assumption, polished samples were examined using an optical microscope at a magnification of $\times 500$. A typical image is shown in Fig. 3. It can be seen from the microscopic photo that most fibers are aligned in the extrusion direction. Similar phenomena were observed for other samples of this batch that are not shown in this paper. Thus, the assumption that the extrusion process can align fibers is qualitatively correct as supported by observations of optical microscopy. Therefore, it could be considered that the fiber distribution is almost unified in the extrusion direction because more paste is available as lubricant at such low fiber volume ratio.

Fig. 4 shows the typical tensile stress and strain curves of Batch #3 with 2% fiber volume ratio in the parallel and transverse directions. Table 4 gives the test results of the specimens of this batch. The most notable effect, comparing with the results of Batch #2 with 1% fiber volume ratio, is

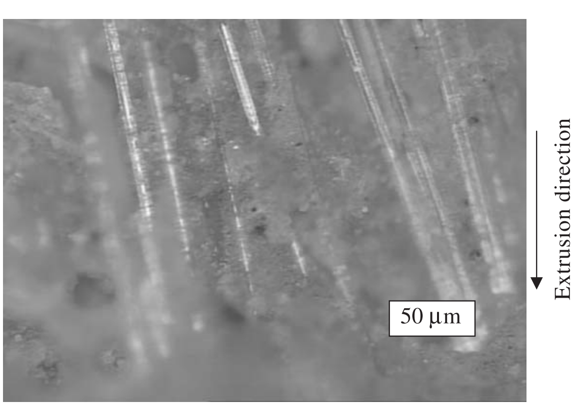

Fig. 3. The fiber distribution with 1% fiber volume ratio ($\times$ 500).

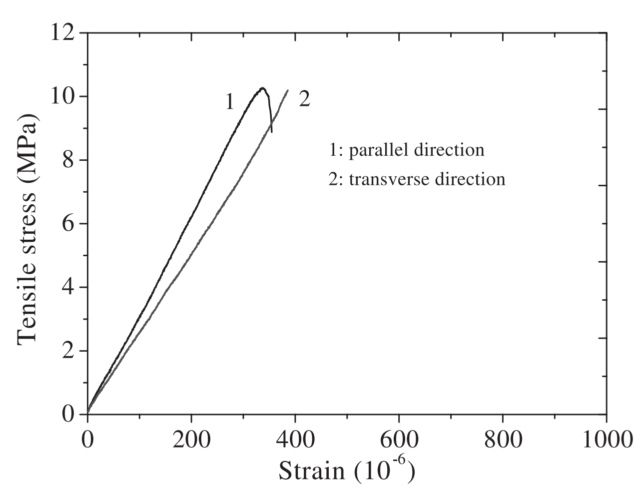

Fig. 4. The tensile stress and strain curves of Batch #3 with 2% fiber dosage.

that the average tensile strengths in the parallel and transverse directions are nearly the same. They are both about 10.6 MPa. These values are very close to that of Batch #2 with 1% fiber in the parallel direction. It seems that with the fiber volume ratio increasing from 1% to 2%, the transverse direction strength improved significantly while the parallel direction strength did not change noticeably. One of the possible explanations of this phenomenon is that the fiber alignment in the extrusion direction is saturated for the effective fiber volume ratio. It means that under the same content of binder and the same W/B (water/binder) ratio, more fibers show a 2-D distribution during the extrusion process. This may be attributed to less paste being available for lubrication when the fiber volume ratio increased. However, one benefit of this is that two-way 'slabs' can be produced rather than just one-way 'slabs' under this condition. To verify fiber distribution, optical microscopic observations were carried out again. The microscopic investigations indicate that fibers showed more two-way distribution tendency as compared with the 1% fiber case. Fig. 5 shows a typical photo of such kind of two-way fiber distribution. This phenomenon was very common in the investigated samples, and it is consistent with the assumption mentioned above. However, no accurate theoretical predictions are available for fiber alignment during the extrusion process.

The test results of Batch #4 with 4% fiber volume ratio are shown in Table 4, which further confirm the above assumption. The typical tensile stress and strain curves of this batch in parallel and transverse directions are shown in Fig. 6. The test results of Batch #4 in Table 4 demonstrate very close average tension strengths in the transverse and parallel directions, namely, 11.5 and 11.4 MPa, respectively. Moreover, the average parallel strength only increases by 8% comparing with those of Batch #3 and Batch #2 having 2% and 1% fiber volume ratio. Similarly, the average transverse strength only increases by 8% comparing with that of Batch #3 with 2% fiber case. Therefore, it is not feasible to increase the strength of the extrudate just by raising the fiber volume ratio, especially when the fiber volume ratio reaches a certain amount. This amount may be considered as a saturated value of the fiber volume ratio. Certainly, this value varies with the materials, mixing proportion and extrusion parameters. Depending on experimental results presented in this paper, the saturated value of the glass fiber volume ratio should be around 2%. Fig. 7 presents the relationship of the fiber volume ratio with tension strength of extrudates and the aforementioned saturated point. The effect of fiber volume ratios on enhancing tensile strength of extrudates can be clearly seen from the figure.

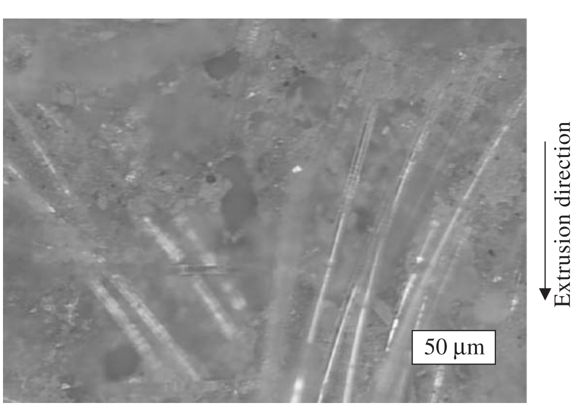

Fig. 5. The fiber distribution with 2% fiber volume ratio (× 500).

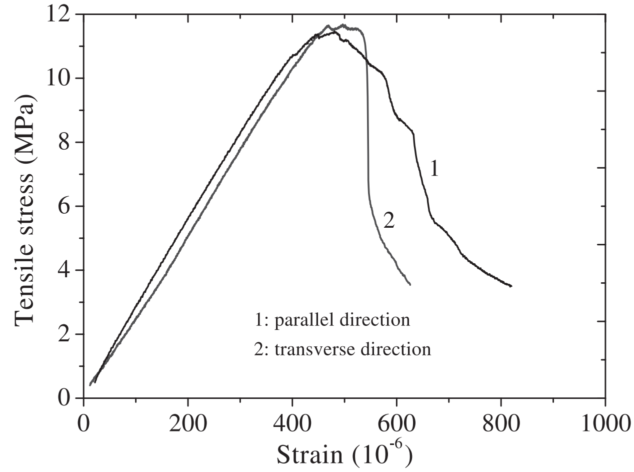

Fig. 6. The tensile stress and strain curves of Batch #4 with 4% fiber dosage.

However, it should be emphasized that this saturated value only refers to the tensile strength of the extrudates. As can be found from the test results of Batch #2, Batch #3 and Batch #4 in Table 4, the average peak strain increased as the fiber volume ratio increased. When the fiber volume ratio reached 4% (Batch #4), the average strains at peak stress in the parallel and transverse directions are around 4.8×10^{-4} mm/mm that are about 30% higher than that of Batch #3 with 2% fiber volume ratio in the parallel direction and 24% in the transverse direction. Furthermore, specimens of Batch

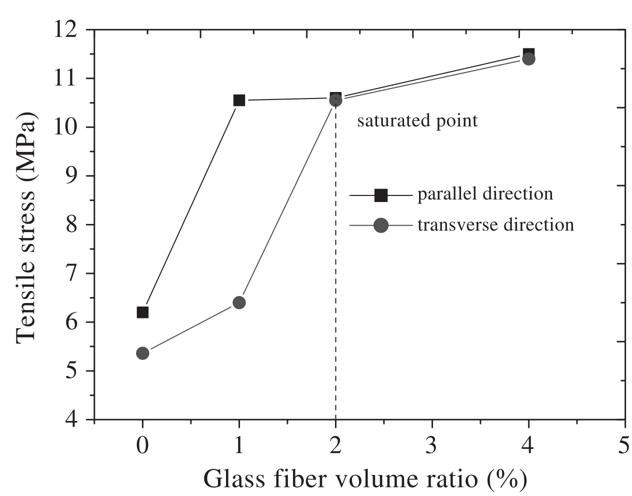

Fig. 7. The relationship of tensile strength with glass fiber volume ratio.

#2 with 1% fiber (Fig. 2) and of Batch #3 with 2% fiber (Fig. 4) show a brittle failure mode, occurred right at the peak stress, and no postpeak response was observed under the current control scheme. However, a specimen of Batch #4 with 4% fiber (Fig. 6) shows good postpeak behaviour using the same control method. It means that ductility and postpeak toughness of the specimen was largely improved as the fiber volume ratio increased to 4%. Thus, it is very effective to increase the toughness and to change the failure mode of the extrudates by adding more fibers than the saturated value regardless of its strength increasing limitation.

It may be an efficient method to improve transverse direction properties by coating polymer on the surface of the extrudate when sufficient fibers could not be added because of technical difficulty or mixing proportion constraints. Fig. 8 shows the tension stress and strain curves of a specimen with 1% fiber volume ratio after surface treatment by epoxy. The experimental results in Table 4 show that the average transverse strength and strain were increased greatly in the case of the 1% fiber volume ratio. The average transverse strength is about 53% higher than that of the case without coating polymer. The tensile strength of epoxy is 20 MPa (measured beforehand), and it has a large peak strain, about 53.1×10^{-4} mm/mm. So the epoxy used for surface coating is more ductile than extrudates. The average thickness of the epoxy layer is 0.20 mm, which can be observed from the cross section. As for the average tensile strength in the extrusion direction, the difference in the average peak stress between coated and uncoated specimens is 1.17 MPa. But for the average transverse strength, the total increase in tensile strength is 3.42 MPa. After deducting the direct contribution of epoxy layer through rule of mixture, there is about an additional increase of 1.68 MPa in the transverse direction, around 26% combination efficiency. This might be attributed to the improvement of surface voids, which could cause stress concentration and

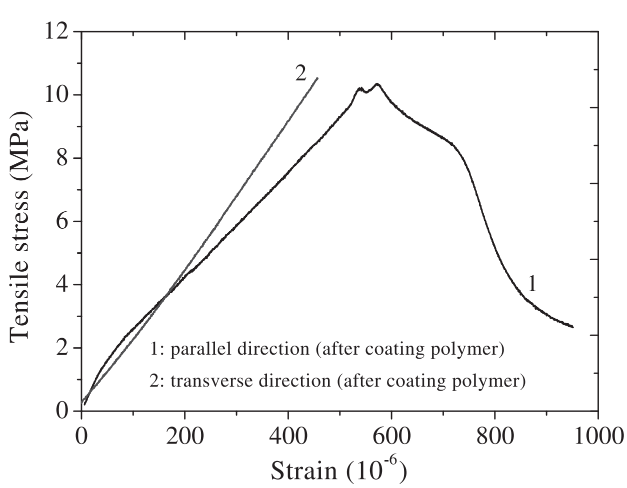

Fig. 8. The tensile stress and strain curves of Batch #2 with 1% fiber dosage after coating polymer.

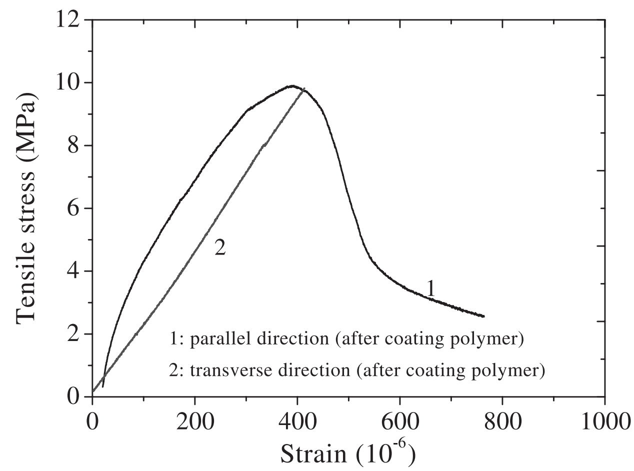

Fig. 9. The tensile stress and strain curves of Batch #3 with 2% fiber dosage after coating polymer.

early fracture, by the pervasion of polymer. This effect offsets the fiber scarcity in the transverse direction when the fiber volume ratio is lower. As for the increase of peak strain and toughness due to epoxy coating, it can be attributed to the lower elastic modulus of polymer, 3.7 GPa in average, which is less than that of the extrudates with an average modulus of elasticity of 24 GPa. When the fiber volume ratio increases to a higher value, 2% for Batch #3, the tensile strength enhancing effect after polymer coating is not so significant as the 1% fiber case (Table 4). But the average peak strain is still increased, especially the peak strain in the parallel direction, at which a 17% increase is observed. Typical tensile stress and strain curves of the specimen of Batch #3 after polymer coating are shown in Fig. 9. The figure indicates that the postpeak toughness is increased. Polyester was also used for surface coating instead of epoxy. Similar results were observed from these polyester-coated specimens. And polyester coating also shows some improved ability of tensile strength and postpeak toughness.

4. Conclusions

The tensile behaviours of fiber-reinforced extrudates have been studied experimentally in both extrusion direction and transverse direction. The test results support the following conclusions.

The extrusion process plays an important role in aligning the fiber in desired directions, especially for a small fiber volume ratio (1% in this study).

The tensile strengths have a big difference at parallel and transverse directions for the extrudate with a small fiber volume ratio (1%), due to the alignment orientation of the fibers.

When the fiber volume ratio reaches a saturated point (2% in this study), the fiber distribution in the transverse direction increases remarkably. As a result, the tensile strengths in two directions become close. It is not feasible to further increase the fiber volume beyond the saturated point just for an increase of the tensile strength of the extrudates. However, the increased fiber volume can enhance the toughness and peak strain.

Surface coating using epoxy and polyester on the extrudate can increase the tensile strength of the extrudate in the transverse direction with a low fiber volume ratio.

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