JOURNAL OF MATERIALS SCIENCE 33 (1998) 2013–2017

Compressive and tensile behaviour of carbon fibres

M. MIWA, Y. MORI, A. TAKENO, T. YOKOI, A. WATANABE
Faculty of Engineering, Gifu University, Yanagido 1-1, Gifu, Japan 501-1193
E-mail: miwa@apchem.gifu-u.ac.jp

Attempts have been made to discuss the fibre axial tensile and compressive behaviour of several carbon fibres prepared from different precursors, and surface- and/or sizing-treatments. With all fibres, the number of breaks increased with increasing tensile or compressive strain, and remained constant beyond a certain strain. The constant number of breakages based on the precursor differed remarkably in compression, whereas those based on the surface- and/or sizing-treatments differed remarkably in tension. In tension, the PAN-based fibre could be broken with a somewhat greater ease than the pitch-based fibre, while in compression, the pitch-based fibre could be broken with somewhat greater ease than the PAN-based fibre. © *1998 Chapman & Hall*

1. Introduction

The relationship between the mechanical properties of composites in tension and those of fibres used as reinforcements has been studied both experimentally and theoretically in fairly great detail. However, in spite of the fact that the compressive characteristics of composites depend on the characteristics of the reinforcing fibres, there has been virtually no study of the mechanical properties of composites in compression.

We have reported a method for measuring the compressive strength of fibres, i.e. if a sufficiently long fibre is embedded near the surface of a rectangular beam and the system is subjected to a tensile (or compressive) strain rather than a fibre ultimate strain, according to the bending method, the fibre eventually breaks into many pieces. By measuring the lengths of the broken pieces, the axial compressive strength of the fibre can be estimated in cases where both the tensile strength of the fibres is assumed to be uniform [1, 2] and where it is assumed to be variable [3, 4].

Using the latter method, we estimated the compressive strengths of carbon, aramid and polyarylate fibres. It was found that the estimated compressive strength of PAN-based carbon fibres was higher than pitch-based ones, and that of carbonized fibres (higher strength type) was higher than graphitized ones (higher modulus type) [3, 5]. Moreover, the axial fibre compressive strength was approximately 10%–60% of the tensile strength [3]. With carbon fibres, it increased with increasing degree of orientation or face spacing of the crystal and increased with decreasing crystal size [5]. In addition, it increased with decreasing fibre diameter [6], and it apparently increased by surface- and/or sizing-treatment [7]. Also, using the three-point bend method, we measured the breaking strain of fibres and reported that the compressive breaking strain was higher than the tensile breaking strain [8].

As mentioned above, the ultimate characteristics (compressive breaking strength and strain) of fibres have been recently examined. However, there have been no studies of early compressive behaviour of the reinforcing fibres.

Using our proposed method [1–7], in this work, the compressive and tensile behaviour of several carbon fibres prepared from different precursors, and surface- and/or sizing-treatments are discussed.

2. Experimental procedure

The fibres used were two kinds of PAN-based fibres (higher strength type T-300, and higher modulus type M-40, Toray) and four kinds of pitch-based fibres (higher modulus type HM, experimental samples of Tonen). HM-I was untreated, HM-II was surface-treated, HM-III was sizing-treated, and HM-IV was both surface- and sizing-treated. The mechanical properties of these fibres are shown in Table I. The T-300 and M-40 fibres were surface- and sizing-treated.

Rectangular specimens were prepared for measuring compressive strain under the same conditions as reported in a previous paper [1–8]. The 100 parts epoxy resin (Epikote 828, Yuka Shell) and 10 parts amine-type curing agent (S-Cure 661, Kayaku Nuri) were mixed. This mixture was agitated thoroughly and then defoamed. Then, it was poured into a mould holding a fibre at a constant tension in the neighbourhood of the surface of a rectangular specimen and subjected to curing at 40 °C for 17 h.

The specimens prepared in this manner were measured for compressive strain, i.e. each specimen was subjected to a compressive strain at a drop rate of the upper heads of 10 mm min^{-1} using the four-point bending method under the same conditions as reported in previous papers [1–6]. The drop, y, of upper heads required for a constant compressive

TABLE I Mechanical properties of fibres (at 20 °C)

Materials			Tensile strength (GPa)	Young's modulus (GPa)	Breaking strain %	Diameter (μm)
Carbon fibre	PAN	T-300	3.50	206	1.7	7.1
		M-40	2.88	388	0.80	7.1
	Pitch	HM-I	3.33	510	0.68	9.9
		HM-II	3.44	480	0.74	9.8
		HM-III	3.39	505	0.67	9.9
		HM-IV	3.53	516	0.67	10.0
Epoxy resin			0.068	1.67	9.3	–

strain, ε_f, is given by the following equation according to the bending theory

$$y = \frac{\varepsilon_f}{6h'} s(3L - 4s) \quad (1)$$

where h' is the distance between the fibre and the neutral axis, L is the span length, and s is the distance between the lower supporting point and the upper loading head.

For comparison, the behaviour in tension was examined. Measurements in compression and tension were made at 40 °C. In this experiment, using the three-point bend method (the fibre strain is maximum at the upper loading point and decreases linearly with the distance from the upper loading point, and is zero at the lower supporting points) as described in a previous paper [8], the fracture strains of the fibres were preliminarily measured. The fibre strains were changed in steps according to the obtained results.

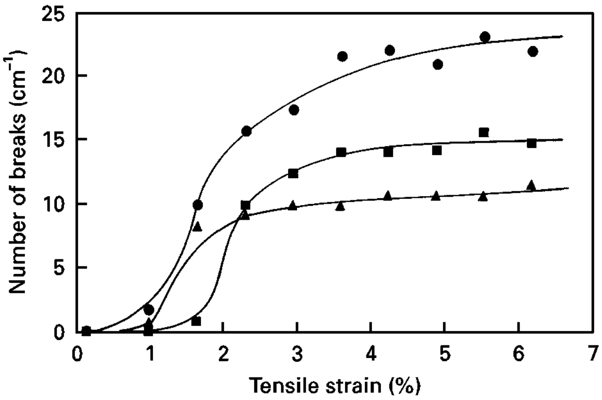

Figure 1 Relation between tensile strain and number of breaks per unit length for carbon fibres prepared from different precursors: (●) M-40, (▲) HM-IV, (■) T-300.

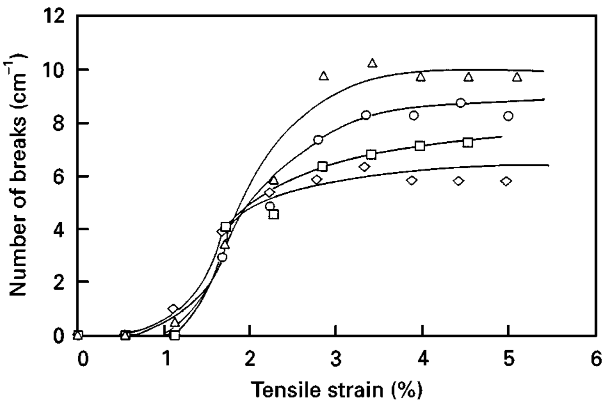

Figure 2 Relation between tensile strain and number of breaks per unit length for pitch-based carbon fibres with different surface- and/or sizing-treatments: (◇) HM-I, (○) HM-II, (□) HM-III, (△) HM-IV.

3. Results and discussion

Typical fracture patterns of fibres of specimens subjected to compression or tension by the above-mentioned method were the same as those reported in a previous paper [2]. For all carbon fibres, the breaking points could be clearly observed. Next, the number of breaks was examined.

The relationships between the number of breaks, N_t, per unit length and tensile strain, $(\varepsilon_f)_t$, are shown in Figs 1 and 2. Fig. 1 shows the results of fibres based on different precursors (whose fibres were both surface- and sizing-treated), while Fig. 2 exhibits the results based on the different surface- and/or sizing-treatments. For the higher strength type T-300 sample, the fibre begins to break at approximately $(\varepsilon_f)_t = 1.5\%$, and for the higher modulus type M-40 and HM-IV, they begin to break at $(\varepsilon_f)_t = 0.6\%$–$0.7\%$. With these fibres, the number of breaks remains constant beyond approximately $(\varepsilon_f)_t = 3\%$ and ~ 15, 20 and 10 cm^{-1} for T-300, M-40 and HM-IV, respectively. Calculation of aspect ratios L/d (fragment length/fibre diameter) are almost identical, i.e. $L/d = 280$, 210 and 290, respectively.

In Fig. 2, in spite of different surface- and/or sizing-treatments, the breaking tendency is almost the same, i.e. the fibres begin to break at approximately $(\varepsilon_f)_t = 0.6\%$–$0.7\%$ and the number of breaks remains constant beyond approximately $(\varepsilon_f)_t = 3\%$. However, the constant number of breaks varies remarkably with the surface state of the fibre. The greatest number, $\sim 10\ \text{cm}^{-1}$, of breaks of the fibre HM-IV with both surface- and sizing-treatments could be found, followed by the fibre HM-II with only surface-treatment, and then the fibre HM-III with only sizing-treatment. The untreated fibre HM-I exhibits the smallest number, $\sim 6\ \text{cm}^{-1}$ of breaks.

The relationship between the number of breaks, N_c, per unit length and compressive strain, $(\varepsilon_f)_c$ is shown

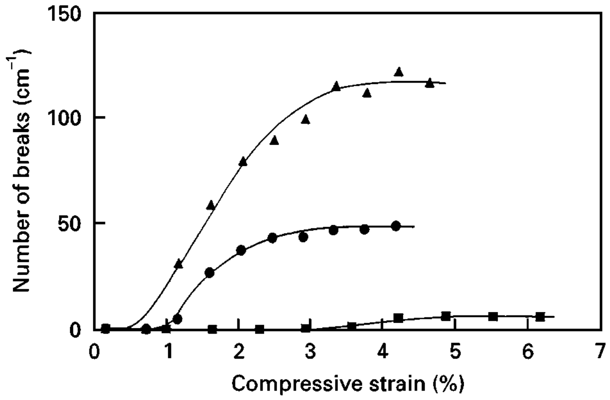

Figure 3 Relation between compressive strain and number of breaks per unit length for carbon fibres prepared from different precursors: (●) M-40, (▲) HM-IV, (■) T-300.

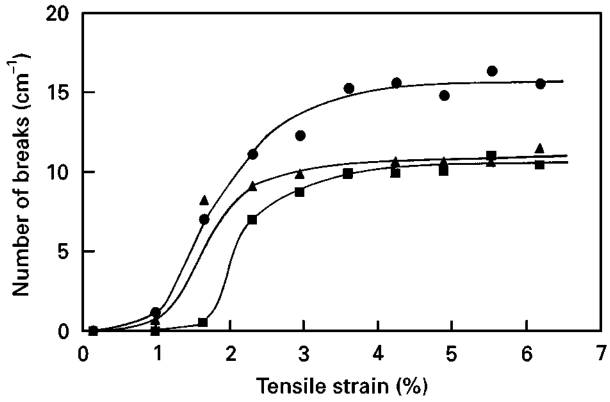

Figure 5 Relation between tensile strain and converted number of breaks per unit length for carbon fibres prepared from different precursors: (●) M-40, (▲) HM-IV, (■) T-300.

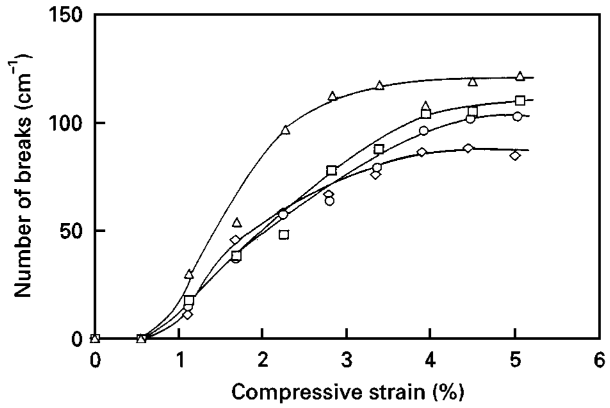

Figure 4 Relation between compressive strain and number of breaks per unit length for pitch-based carbon fibres with different surface- and/or sizing-treatments: (◇) HM-I, (○) HM-II, (□) HM-III, (△) HM-IV.

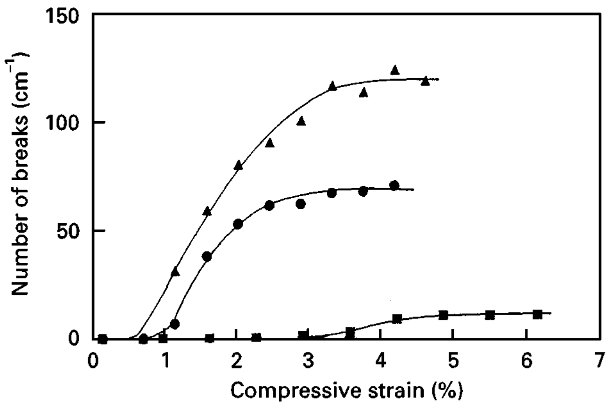

Figure 6 Relation between compressive strain and converted number of breaks per unit length for carbon fibres prepared from different precursors: (●) M-40, (▲) HM-IV, (■) T-300.

in Figs 3 and 4. For the higher strength type T-300 in Fig. 3, no fibre breaks could be observed until approximately $(\varepsilon_f)_c = 2.3\%$. The number of breaks, N_c, thus increased with increasing compressive strain, $(\varepsilon_f)_c$, and remained constant beyond $(\varepsilon_f)_c = 5\%$. For the higher modulus type M-40 and HM-IV, breaks began at $(\varepsilon_f)_c = 0.7\%$ and the number of breaks remained constant beyond approximately $(\varepsilon_f)_c = 2.5\%$ and 3.5%, respectively. The number of breaks, N_c, of the pitch-based fibre, HM-IV, was approximately 1.5 times that of the PAN-based fibre, M-40, (therefore, the aspect ratio of fragment length was almost identical). The value of compressive strain in which the number of breaks was constant, was of the same order as the compressive breaking strain obtained elsewhere [8].

As mentioned above, the fibres undergoing compression began to break according to the same order as when breaking under tension. Therefore, the higher strength type T-300 is also superior to the higher modulus type M-40 and HM-IV in compression.

Fig. 4 shows that, regardless of the in surface state, all the fibres begin to break at approximately $(\varepsilon_f)_c = 0.7\%$, and the number of breaks increases with increasing strain and remains constant beyond $(\varepsilon_f)_c =$ 3%–3.5%. The greatest number, $\sim 120\ \mathrm{cm}^{-1}$, of breaks occurs in the fibre HM-IV with both surface- and sizing-treatments. The untreated fibre I has the smallest number, $\sim 90\ \mathrm{cm}^{-1}$.

If fibres had the same compressive properties, breaks with a larger diameter would be lower in number per unit length, but the aspect ratio of fragment length would be the same. As the diameter of fibres used in this experiment varied with the precursor (Table I), the number of breaks for each fibre was converted with reference to the maximum diameter (10.0 μm). These results are shown in Figs 5 and 6. The numbers of breaks based on the precursor were remarkably different in compression. The constant number of breaks for the PAN-based high-modulus type M-40 was then compared with the pitch-based high-modulus type HM-IV. In tension, the number, N_t, of breaks was $\sim 16\ \mathrm{cm}^{-1}$ for the M-40 fibre and $\sim 11\ \mathrm{cm}^{-1}$ for the HM-IV fibre, i.e. the number of breaks of the PAN-based fibre, M-40, was approximately 1.5 times that of the pitch-based fibre, M-IV. On the other hand, in compression, N_c was $\sim 50\ \mathrm{cm}^{-1}$ for M-40 and $\sim 120\ \mathrm{cm}^{-1}$ for HM-IV, i.e. the number of breaks of HM-IV fibre was approximately 2.4 times that of the M-40 fibre. Accordingly, in tension, the

PAN-based fibre could be broken with somewhat greater ease than the pitch-based fibre, while in compression, the pitch-based fibre could be broken with somewhat greater ease than the PAN-based fibre. It was conceivable that this behaviour was caused by the crystal size of the pitch-based fibres, which are larger than the PAN-based fibres, as reported in a previous paper [6].

As shown in Figs 2 and 4, the numbers of breaks based on the surface- and/or sizing-treatments were remarkably different in tension. Comparing the constant number of breaks for the untreated fibre HM-I with the surface- and sizing-treated fibre HM-IV, in compression, the number of breaks of the HM-IV fibre was approximately 1.4 times that of the HM-I fibre, while in tension, it was approximately 1.7 times.

These results show the efficiency of shear stress transmitted to the fibre through the fibre–matrix interface is the lowest for the untreated fibre HM-I. When the bond existing at the fibre–matrix interface is poor, debonding of the fibre may occur along the fibre–matrix interface at the breaking point, and so the lengths of broken fibre are longer, i.e. the number of breaks is smaller. It is conceivable that this tendency is remarkable in tension where the debonding of the fibre is influenced significantly.

The PAN- and pitch-based fibres used in this study were supplied with different surface- and sizing-treatments by two manufactures. Therefore, it is conceivable that the bond strength at the fibre–matrix interface is different. It was found that the differences in the numbers of fibre breaks shown in Figs 2 and 4, in which the effects of the surface- and sizing-treatments are shown, are smaller than those for the different precursors (Figs 5 and 6). Accordingly, if the bond strength at the fibre–matrix interface was the same, the results shown in Figs 5 and 6 could be slightly changed.

In order to be able to discuss whether breaks occur simultaneously within a narrow strain range or one after another over a wider strain range, the increasing ratio of the number of breaks, i.e. the number of breaks per unit strain (the gradient of the number of breaks–tensile or compressive strain relationships) was examined. The relationship between the number of breaks per unit strain (in Figs 3–6) and the shape parameter, *m*, in a Weibull distribution function, which measures the amount of scatter of the tensile strength and obtained elsewhere [3, 7], are shown in Figs 7 and 8. Under both tension and compression, the number of breaks per unit strain increases with increasing shape parameter, *m*, i.e. the number of breaks per unit strain under both tension and compression correlated to the shape parameter, *m*, in the same manner. Therefore, it was hypothesized that the process of compressive breaking occurred in a similar manner to tensile breaking.

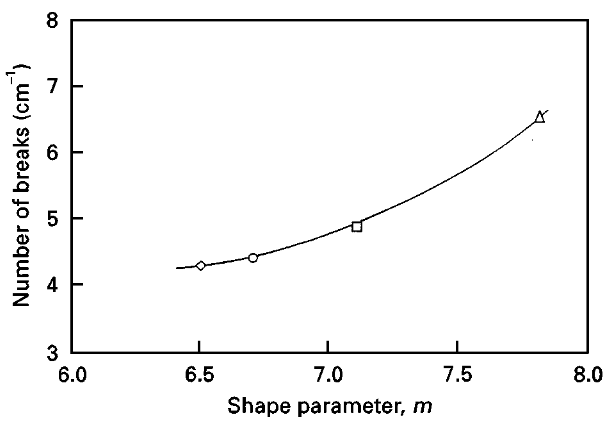

Figure 7 Relation between shape parameter and number of breaks per unit strain in tension for pitch-based carbon fibres with different surface- and/or sizing-treatments: (◇) HM-I, (○) HM-II, (□) HM-III, (△) HM-IV.

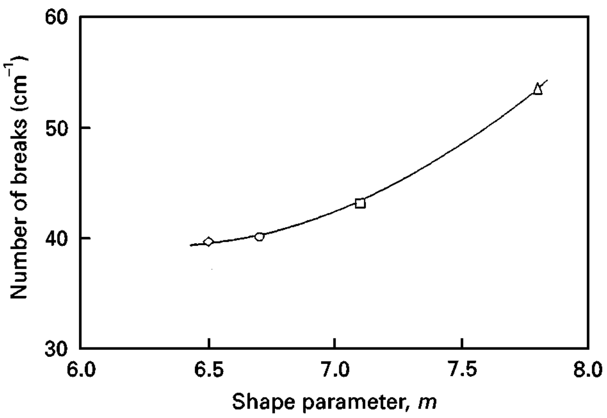

Figure 8 Relation between shape parameter and number of breaks per unit strain in compression for pitch-based carbon fibres with different surface- and/or sizing-treatments: (◇) HM-I, (○) HM-II, (□) HM-III, (△) HM-IV.

4. Conclusion

If a sufficiently long fibre is embedded near the surface of a rectangular beam, and the system is subjected to a tensile (or compressive) strain rather than a fibre ultimate strain, according to the bending method, the fibre eventually breaks at many points. The tensile and compressive behaviour of several carbon fibres prepared from different precursors, and surface- and/or sizing-treatments were discussed.

With all fibres, the number of breaks increased with increasing tensile or compressive strain and remained constant beyond a certain strain. The constant numbers of breaks based on the precursor differ remarkably in compression, while those based on the surface- and/or sizing-treatments differ remarkably in tension.

References

1. M. MIWA, T. OHSAWA, M. KAWADE and E. TSUSHIMA, *Reinf. Plast. Jpn* **35** (1989) 199.
2. T. OHSAWA, M. MIWA, M. KAWADE and E. TSUSHIMA, *J. Appl. Polym. Sci.* **39** (1990) 1733.
3. M. MIWA, E. TSUSHIMA and J. TAKAYASU, *ibid.* **43** (1991) 1467.
4. M. MIWA, A. TAKENO and Y. LIU, *Reinf. Plast. Jpn* **37** (1991) 289.

5. M. MIWA, A. TAKENO, Y. LIU, A. WATANABE, J. TAKAYASU and E. TSUSHIMA, *ibid.* **38** (1992) 433.
6. M. MIWA, Y. LIU, H. TSUZUKI, A. TAKENO and A. WATANABE, *J. Mater. Sci.* **31** (1996) 499.
7. M. MIWA, A. TAKENO, Y. MORI, T. YOKOI and A. WATANABE, *ibid.* **31** (1966) 2957.
8. M. MIWA, E. TSUSHIMA and J. TAKAYASU, *Sen-i Gakkaishi* **47** (1991) 171.

Received 27 January
and accepted 5 December 1997