

THE TENSILE FAILURE MECHANISM OF CARBON FIBERS

Zhong-yu Xu, Hong-bo Liu, Yu-chang Su and Hong-bo Zhang

Department of Chemistry and Chemical Engineering, Hunan University
Changsha, Hunan 410082 P. R. C

INTRODUCTION

Various attempts have been made to produce carbon fibers (CF) with very high tensile modulus while at the same time maintaining or increasing the ultimate tensile strength. This work was to investigate the changes in microstructure and mechanical properties of PAN-based carbon fibers (PAN CF) by graphitizing at temperatures up to 3000°C. The objective of this work was to reveal the relation between the microstructure and the tensile failure mechanism.

EXPERIMENTAL

One kind of Chinese PAN CF was used as samples. Experiments were performed in a 100 kW induction furnace with 2.5 kHz frequency. The inner diameter of the graphite crucible is 170mm and the inner height of it is 470mm. PAN CF samples were wound on the graphite rolls which were put in the constant temperature zone of the crucible. Before heating, the furnace was evacuated to 10^{-2} Pa, then it was filled with pure argon to 0.1MPa. During heating the pressure was maintained by an electromagnetic valve. Six experiments were carried on at different maximum heat treatment temperatures (HTT_{max}). The time (t) for reaching HTT_{max} was also different.

The diameters (d), densities (ρ), tensile strength (σ), modulus (E) and cracking elongation (ε) of all the CF which obtained in above experiments were measured. The data are in table 1. The parameters of graphite microcrystallites in the CF (d_{002} , L_c , L_a , $W_{1/2}$) obtained from above experiments were measured by X-ray diffraction. The data are in

table 2. The parameters of micropores in the CF obtained from above experiments were measured by small angle X-ray scattering (SAXS). L_p is the statistical average size of micropores which are parallel to the axis of CF and L_v is the statistical average size of micropores which are perpendicular to the axis of CF. The data are in table 3.

DISCUSSION

When we apply the tensile stress to a CF, the stress will concentrate on the tips of the microcracks and micropores. According to Griffith's theory[1], the microcrack in brittle materials will extend rapidly, if the elastic strain potential energy is greater than the surface energy for building up two new crack faces. The critical stress for extension is $\sigma_c = (E\gamma/\pi c)^{1/2}$, where E is the modulus, γ is the surface energy of new crack faces, and $2c$ is the initial longitudinal length of the microcrack. From this formula, we can see that σ_c is inversely proportional to the square root of c , and the tensile failure of a CF is determined by the maximum initial longitudinal length of the microcracks and micropores in the CF.

From table 1, we can see the tensile strength of CF decreases with increasing HTT_{max} . Evidently, it is due to the increase of the initial longitudinal length of the microcracks. The microcracks usually exist at the interfaces between graphite microcrystallites and amorphous carbon, because their thermal expansion coefficients are quite different. Therefore, we can use the size of graphite crystallites to represent the initial longitudinal length of microcracks. It must be pointed out that the direction of σ_c is assumed to be

perpendicular to the longitudinal length to be microcrack in Griffith's derivation, thus the tensile failure of a CF is only dependent on the microcracks which are perpendicular to the axis of the CF and independent of the microcracks which are parallel to the axis of CF. From table 2, we can see the magnitudes of the orientational angle of graphite microcrystallites of CF ($w_{1/2}$) are all very small. It means that the graphite layers of microcrystallites in CF are nearly parallel to the axis of CF. The magnitude of L_c decreases with increasing HTT_{max} and is equal to the thickness of graphite layers in microcrystallites. The direction of L_c is perpendicular to the axis of CF, hence the increase of L_c will bring about the increase of initial longitudinal length of microcracks in radial direction of CF and this will cause the decrease of σ of CF. The magnitude of L_a represents the size of graphite layers in microcrystallites. In our experiments, it is nearly unchanged, hence its influence to σ of CF can be neglected.

The micropores in CF decrease the cross section of CF, hence the increase of magnitude of L_v during increasing HTT_{max} (see table 3) causes the decrease of the σ of CF (see table 1). Besides, if we apply the tensile stress to a CF, the micropores will undertake compressive stress in the radial direction of CF. Since the longitudinal length of micropores L_p can be regarded as parallel to the axis of CF (see table 3), the direction of extension of microcracks at the tips of micropores also will be parallel to the axis of CF. Therefore, the increase of L_p during increasing of HTT_{max} does not influence the tensile failure of CF.

CONCLUSION

In the process of graphitizing CF, the microcracks occur and extend at the interfaces between graphite microcrystallites and amorphous carbon. The increase of L_c during increasing HTT_{max} causes the decrease of σ

of CF. The micropores decrease the cross section area of CF, hence the increasing of L_v during increasing HTT_{max} also causes the decrease of the tensile strength of CF. Perhaps the most effective method to prevent L_c and L_v from overgrowing during graphitization is hot stretching.

REFERENCES

1. Zheng-duo Guan, "The Physical Properties of Inorganic Materials" P45, Chinghua University, 1992

Table 1. The relation between the HTT_{max} and mechanical properties of CF

HTT_{max} (°C)	t (min)	d (μ m)	σ (GPa)	E (GPa)	ϵ (%)	ρ (g/cm ³)
original CF		6.28	3.49	227.6	1.63	1.680
2000	14.3	5.58	2.92	279.2	1.12	1.725
2200	16.8	5.83	2.88	297.1	1.03	1.753
2400	21.0	5.87	2.77	319.8	0.91	1.813
2600	25.3	5.75	2.58	340.3	0.79	1.863
2800	31.0	5.56	2.54	381.4	0.72	1.883
3000	38.7	5.41	2.52	404.4	0.68	1.935

Table 2. The relation between the size and orientation of graphite crystallites in CF

HTT_{max} (°C)	d_{002}	L_c	L_a	$W_{1/2}$
original CF	3.570	13	20	20.2
2000	3.466	27	44	13.9
2200	3.453	31	50	13.2
2400	3.417	38	52	11.1
2600	3.397	53	54	9.9
2800	3.390	64	55	8.5
3000	3.383	69	55	8.1

Table 3. The relation between the HTT_{max} of CF and the size of micropores in CF

HTT_{max} (°C)	original	2200	2600	3000
L_v (Å)	20.3	28.7	43.0	52.0
L_p (Å)	87.0	114.6	135.6	169.6
L_p (Å) / L_v (Å)	4.29	3.99	3.15	3.26