The Strength Distribution in Etched Carbon Fibers

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Abstract. There are two distinct types of distributions of strength among types of etched carbon fibers. Some types of fibers have a strength which changes as the surface is etched away. For other fibers, strength gradients were not observed. These strength distributions are related to microstructures.

Carbon fibers often show a variation in axial properties across the fiber diameter which leads to modulus gradient[1,2] and residual stresses[1]. This paper discusses the strength distribution of etched fibers and the relationship to microstructure. Hercules HMS, HTS, AS-4 and AS carbon fibers and Union Carbide T-300 fiber were thinned by electrochemical etching. The strength of single filaments were measured at a gauge length of 25.4mm by using test conditions[2,3] that allowed recovery of the primary fracture surface. The failed filament ends were observed using SEM.

The surface layer of carbon fibers often has higher local modulus[4]. The strength will change upon removal of the outside layer, and the strength distribution will depend on the magnitude of local modulus, residual stress and flaw mechanism. The strength distribution of etched HMS, HTS, AS-4, AS and T-300 fibers are shown in Fig. 1(a)-(e). The group mean values were properly compared using Bartlett's test, ANOVA, Dunnett's test and the t-test[5]. For HMS fibers, (Fig. 1(a)) the mean strength of as-received fiber is higher than when etched. This finding is related to the structure of HMS fiber and the effect of residual stress distribution within the fiber. Because those layers of higher local modulus are etched away gradually, the average modulus of the remaining fiber becomes smaller. Simultaneously, the residual stress is relieved and the surface compressive stress becomes smaller. In terms of a flaw mechanism, most of the fracture surfaces of this high modulus fiber showed gross interior voids (see Fig. 2(a,b)) and fracture is believed to originate from these voids. Assuming constant strain at failure for the flaw, the strength drops as the high modulus sheath is etched away. The mean strengths of the group pairs (2,3), (3,4), (4,5) and (5,6) showed them to be the same. The strength of HMS fiber drops upon surface sheath removal and then stays constant (as shown in Fig. 1 (a)).

HTS carbon fiber has less modulus gradient [4] and a lower HTT than that of HMS fibers; therefore, less residual stress is expected. The strength distributions of HTS fibers are shown in Fig. 1(b).

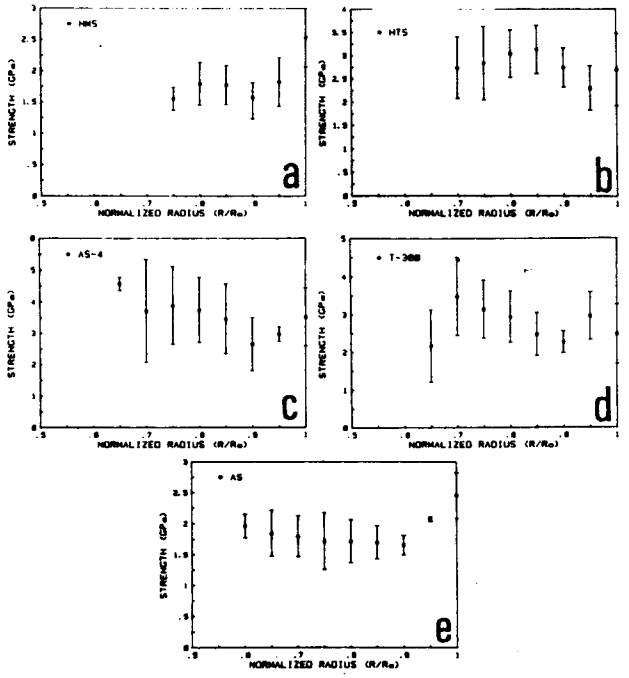
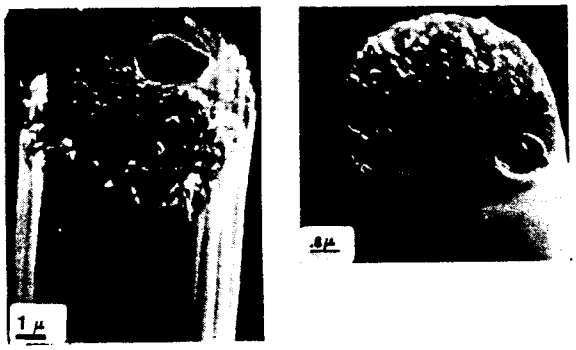


Fig. 1 The Strength Distribution of Carbon Fibers (a) HMS (b) HTS (c) AS-4 (d) T-300 (e) AS

Although the nominal mean values of strength in etched fiber groups are higher than those of as-received fibers, they are not significantly different statistically. The fracture surfaces of HTS as-received fiber (Fig. 3) showed that failure initiated from a surface flaw. No serious interior-voids, as in HMS fibers, were observed. Since less residual stress is present and no internal flaws are apparent, fracture is likely to initiate from flaws on the surface. The slight increase in strength might be due to removal of flaws upon etching.

The modulus gradient of type A (AS-4, AS and T-300) fibers are among the lowest of the fiber types[4]. Since the HTT of type A fibers



(a) (b)

Fig. 2 SEM fractography of HMS Carbon Fiber (a) As-received (b) Etched

is only 1100°C, the effect of residual stress is expected to be low. The group mean strengths of AS-4 are all equal (Fig. 1(c)). The grand mean strength is 3.47 GPa (504 Ksi) across the diameter down to a radius ratio of .65 with a pooled standard deviation of 1.04 GPa (150 Ksi). The same results as with AS-4 fibers are found in T-300 fibers. However, the strength of AS fibers did not follow the same trend as other type A fibers such as AS-4 and T-300. The mean strength of AS as-received fibers is only 2.45 GPa (355 Ksi), which is quite low compared to manufacturer's data.

In general, there are two distinct types distributions of strength among types of etched carbon fibers. HMS have a strength gradient when etched, while type II and type A do not. These strength distributions are related to the microstructure of the fibers. For HMS fibers with a skin/core structure, the strength is higher at the surface, then degrades towards the core, as the surface layer was removed. In addition, due to the relief of residual stress, the decrease in modulus and the exposure of the interior flaws to the surface after etching, the strength of the etched fiber decreases. Interior voids are found in HMS fibers which are the main failure initiator (see Fig. 2). For type II and type A no significant variations were observed in fiber strength as the surface layer was removed. Surface flaws are the main failure initiator (see Fig. 3 & 4). Finally, no serious interior voids were found in type II and type A fibers.

Fig. 3 The failure initiated from surface flaw for HTS as-received carbon fibers.

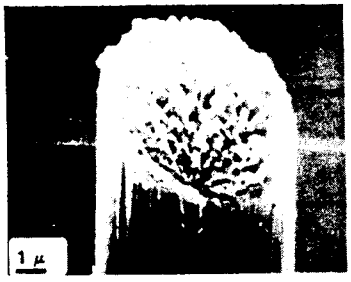


Fig. 4 SEM fractography of as-received carbon fiber showing fracture pattern originating at surface flaw.

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