ON THE MECHANICAL CHARACTERISTICS OF COMMERCIAL CARBON FIBERS

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Introduction

The use of carbon fibers in composites is the most successful commercial application of solid carbons within the past few decades. Notwithstanding their success, questions remain regarding how to tailor and optimize their properties. Addressing these questions is important in order to develop improved composites and new applications for carbon fibers [1].

Being a vertically integrated supplier of advanced composites, Hexcel is unique in its ability to apply decades of technology to address every single aspect of the carbon fiber and composite production process. This study examines some key aspects known to impact the performance of carbon fibers. A more comprehensive assessment of structure-property relationships will be given elsewhere [2].

Experimental

Commercial fibers were produced from various precursors (polyacrylonitrile, rayon, mesophase and isotropic pitches, and acetylene gas) using methods described in the literature [3-5]. Mechanical, structural, thermal and chemical properties of the fibers were determined using standard methods [6,7] and were compared to historical results [8].

Results and Discussion

The performance of composites derived from carbon fibers is closely related to the properties of the fibers themselves. These properties are in turn dictated by a multitude of precursor and conversion variables available to fiber and composite manufacturers [9-11]. These variables interact in diffusion and reaction mechanisms differently upon conversion, as can be conveniently deduced from materials selection charts such as that shown in Figure 1. In Figure 1 the toughness (G_{ic}) of over 100 fibers derived from different precursors is plotted against the % strain-to-failure (ε) of the fibers. The crack length was assumed to be a fraction proportional to the diameter of the filaments. This assumption allows all data points to fall on a single line, as opposed to widely scattered data that results from assuming a constant crack length in all cases. It follows that crack lengths are proportional to fiber diameters regardless of the precursor chosen. The exceptions to this rule are rayon-based fibers, which are weaker (probably because they have relatively large crack lengths), and carbon whiskers, which are tougher (because of their multiple yet small crack nucleation sites or steps).

Figure 1 also shows contours of constant Young's modulus of elasticity, E. In commercial fibers, toughness is seen to be gained at the expense of E. This is why commercial fibers are termed HS (for high strength) or HM (for high modulus), with a more ideal combination of properties being displayed by short graphite whiskers. Figure 1 thus suggests that optimum HS-HM fiber properties are attainable, but they might require important changes in fiber manufacturing conditions.

Given the impact that flaws and structural discontinuities have in determining fiber properties, relatively little has been published on relating surface area and porosity characteristics to ultimate fiber performance. Surface areas of carbon fibers are reported to be low (< 10 m^2/g) when tested by external fluid probing methods like gas sorption or mercury porosimetry. Yet typical fibers are rich in elongated (needle-like) but "closed" pores, as determined by small-angle X-ray scattering (SAXS), or by gradually exposing the pores to external fluids by controlled oxidation [12]. The walls of these narrow pores can expose internal areas > 100 m^2, and influence fiber properties, such as that shown with E in Figure 2. Figure 2 shows that E decreases with increasing (internal) area and porosity, as expected [10,11]. However, smooth elongated pores also serve as crack propagation stoppers, much like weak interfaces do in composites. In fact, treating carbon fibers as if they were composites of crystalline (strong) and non-crystalline (weak) components allows the derivation of a simple model [2] from which the ratio of adhesion to cohesion strengths (R_{ac}) can be obtained:

$$R_{ac} = (8/\pi)(E_a/E_c)(L_c^2/L_a)(\cos[\phi])/d_{002} \quad (1)$$

where E_a/E_c is the ratio of adhesive to cohesive energies, L_c and L_a are the average crystallite dimensions, ϕ is the orientation angle, and d_{002} is the interplanar layer spacing. This ratio is related to the toughness of the fibers. As pointed out by Gordon [13], effective crack stopping in non-metallic materials requires planes of weakness meeting the path of the propagating cracks. However, there is a balance between how much the toughness of a material can be enhanced by weak interfaces before the material as a whole is weakened. This balance is given by the ratio R_{ac}, as illustrated in Figure 3. If R_{ac} is low (say < 0.2, as expected in theory [13]), the planes of weakness within it will act as effective crack stoppers, but the toughness will be low due to the high concentration of planes of weakness or pores. Conversely, if $R_{ac} > 0.2$, the material will behave as a continuum and would exhibit brittle fracture upon crack propagation. The fact that the toughness of many commercial fibers is lower than might be anticipated from their R_{ac} values is likely to be due to external and internal flaws introduced in the fibers during their manufacturing processes.

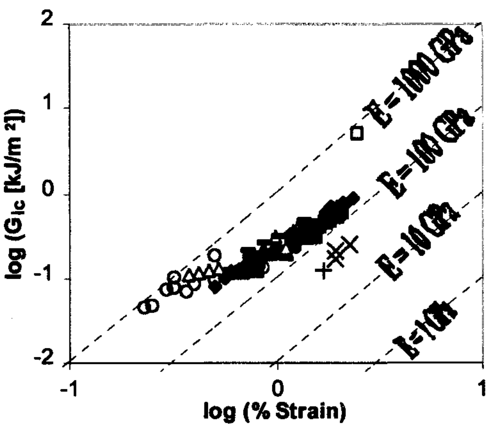

Figure 1. Toughness (G_{Ic}) vs. % strain for commercial carbon fibers [4,8]. Precursors: filled symbols, PAN; open symbols = pitch; crosses, rayon; hyphens, vapor-grown; grey square = graphite whiskers [9]. Contours represent lines of constant Young's modulus of elasticity.

References

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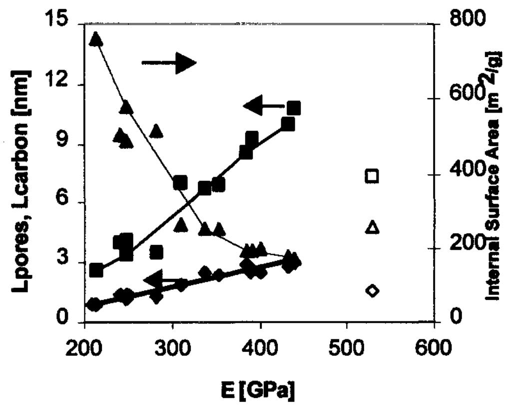

Figure 2. Relationship between Young's modulus (E) and physical parameters (surface area and pore structure) of a commercial carbon fiber. Adapted from Refs. 10 and 11. Symbols: ♦, L_{pores}; ■, L_{carbon}; ▲, surface area; closed symbols = fibers subjected to various heat treatments; open symbols = commercial product.

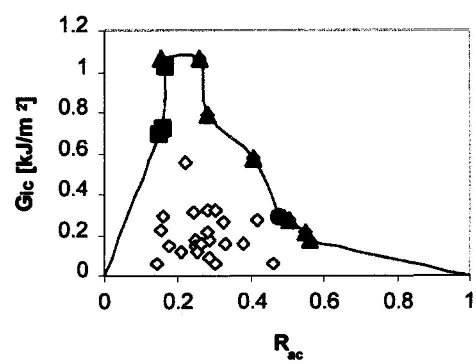

Figure 3. Toughness (G_{Ic}) vs. R_{ac} for PAN-based commercial carbon fibers. Symbols: ■, Hexcel; ▲, Toray; ●, Toho; ◊, others.