Cryogenic properties of polymer composite materials – a review

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Polymer composite materials are used in a wide variety of cryogenic applications to replace metals because of their unique and highly tailorable properties. In order to develop high performance polymer composites for cryogenic applications, it is necessary to understand how polymer composites behave at cryogenic temperatures and how their cryogenic properties are affected by factors such as filler content and matrix type etc. This review presents detailed discussions on the effects of various factors on the cryogenic mechanical and thermal properties at the unique operating environments.

INTRODUCTION

Polymer composite materials are being increasingly employed to manufacture structural components that are exposed to low temperature environments in space and superconducting applications [1-18]. The involved composites include fiber and particle reinforced thermoplastic and thermosetting polymer composites. The cryogenic applications of polymer composites can be classified as support structures, vessels and electrical insulation. Fundamental mechanical, thermal and electrical requirements should be met by polymer composites for specific cryogenic applications. Composites are subjected to uncommon synergetic conditions in cryogenic environments: high mechanical stress by electromagnetic force, thermo-mechanical stress caused by the cryogenic environment, phase transition of coolant and high energy radiation etc. The cryogenic mechanical and thermal properties of polymer composites are important in cryogenic applications. In order to meet the requirements of mechanical and thermal properties for cryogenic applications, various polymer composites have been studied extensively. This review presents detailed discussions on the effects of various factors on the cryogenic mechanical and thermal properties at the unique operating environments.

MECHANICAL PROPERTIES

<u>Fiber reinforced plastic composites</u>

Fiber reinforced plastics (FRP) were widely used in cryogenic applications because of their high strength, high stiffness, low weight and good thermal properties. Fiber type, fiber direction and interfacial properties play very important roles in determining the mechanical properties of FRP.

Hartwig et al [19] discussed the influence of the fiber type on the fatigue behavior of unidirectional cross-plied composites. The fatigue behavior was studied on composites with the same epoxy matrix but different types of fibers. The fatigue behavior at 77 K of epoxy composites with different fiber types (carbon AS4, ceramic Al_2O_3 and Kevlar 49 fibers etc) is shown in Figure1 (so-called S-N curves, namely stress-load cycles diagram). The highest strength is achieved for carbon fiber composites.

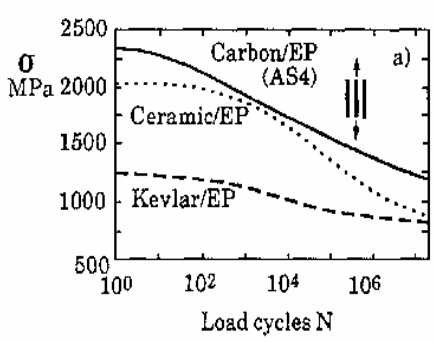

Figure1. S-N curves of unidirectional fiber reinforced epoxy composites at 77 K [19]

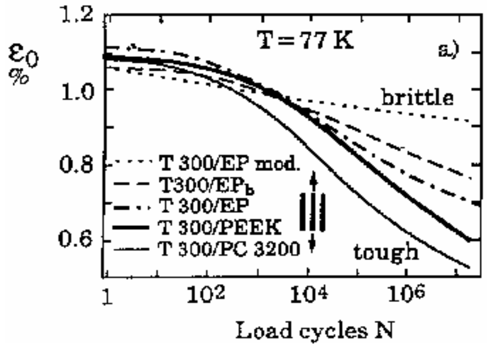

Figure 2. Strain-life curves of UD carbon fiber composites under tensile loading [19]

Composites having a poor transverse strength are sensitive to microcracks induced in the matrix. The formation of microcracks at fatigue loading is different for different matrix types, and so is the fatigue endurance limit. In Figure 2 the influence of the different matrix was shown on the fatigue behavior of unidirectional carbon fiber reinforced plastic (CFRP) composites by strain-life diagrams [19].

The influence of fiber directions on the mechanical properties of FRP wasstudied by Hussain et al [20] and Baynham et al [21].The mechanical properties of FRP in parallel to fiber direction is higher as the properties are mainly controlled by the fibers. However, the mechanical properties of FRP in transverse to fiber direction is inferior because the properties are mainly governed by the properties of the matrix and the fiber-matrix interface. Hussain et al suggested that Young's modulus in the transverse to fiber direction can be improved by incorporating Al_2O_3 particles into the matrix (Figure 3) [19]. The Al_2O_3 filler dispersions act as secondary reinforcement.

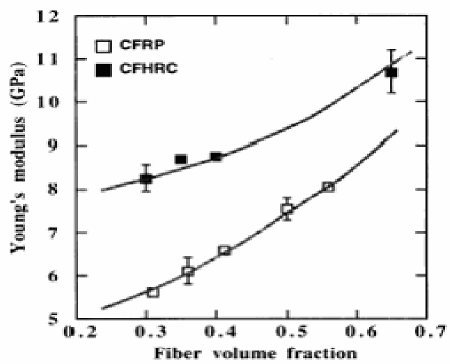

Figure 3. Young's modulus in the transverse to fiber direction as a function of fiber content □ CFRP [19]
■ CFHRC (CFRP contained 10 vol % Al_2O_3 particles)

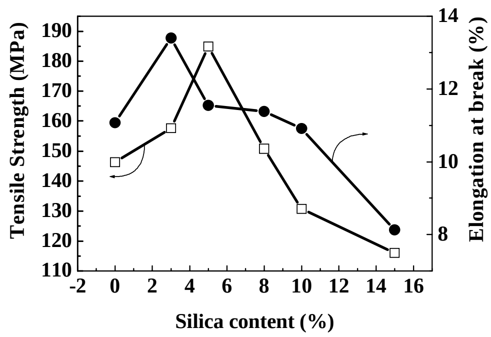

Figure 4. The tensile properties at 77K of polyimide/silica hybrid films

Particulate reinforced polymer composites

The mechanical properties at liquid nitrogen temperature of various particle reinforced polymer nano-composites have been studied recently by our research group. These nanocomposites include epoxy/SiO_2, polyimide/SiO_2 and polyimide/clay nanocomposites. It has been shown that the cryogenic mechanical properties can be effectively enhanced by incorporating proper quantities of nano-fillers into the matrix (as an example, see Figure 4) [22].

THERMAL PROPERTIES

Thermal properties of polymer composites are important design parameters in cryogenic applications. The factors influencing the thermal expansion and conductivity of composites at low temperatures will be reviewed below.

Thermal expansion

Nadeau and Baschek et al [23,24] studied the factors influencing the thermal expansion. The influencing factors include thermal cycling, mechanical creep loading and mechanical geometrical shape (plates, half-tubes and tubes). The results showed that the expansion was influenced in different manners by thermal cycling and mechanical creep loading. The influence of thermal cycling on expansion was shown in Figure 5. [23]. The result indicated that the integral thermal expansion was lowered by more than 20%. In addition, the influence of thermal cycling on the coefficient of thermal expansion was significant as well. The influence of mechanical creep loading on expansion of carbon reinforced plastics with different fiber angles was also reported. The results showed that in the range of $\omega = \pm 30°$ the thermal expansion was not sensitive to the change of the fiber angle.

Thermal conductivity

The thermal conductivity of fiber reinforced plastic is much lower than that of metals and shows anisotropic. Hence, in general, it is much more difficult to dissipate heat in fiber reinforced plastic than in metals. This is an important consideration in some situation [25].

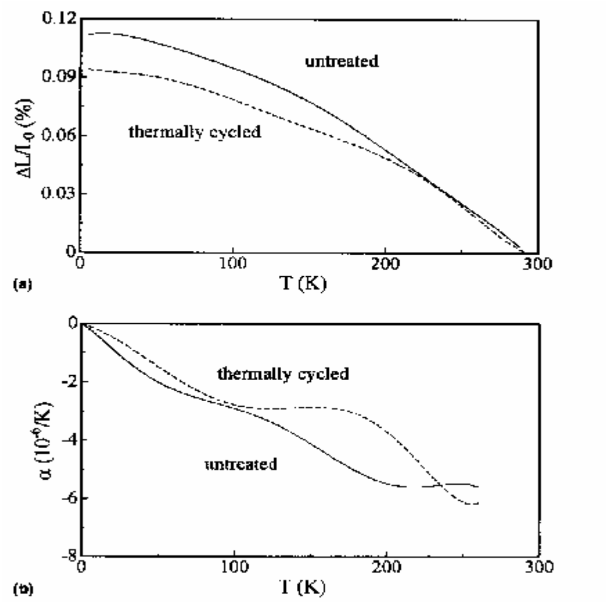

Figure 5. Thermal expansion of carbon fiber reinforced plastics (±30°) before and after thermal cycling (100 cycling,77-293 K). (a)Integral thermal expansion; (b) coefficient of thermal expansion [23]

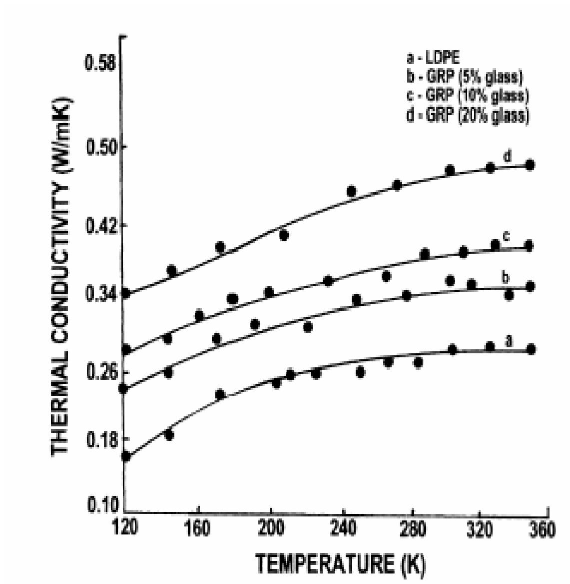

Figure 6 The thermal conductivity of LDPE and GRP composites [25]

SUMMARY

Polymer composite materials are being increasingly employed for cryogenic applications. Cryogenic properties of the polymer composites are influenced by a number of factors. This review has given detailed discussions on the effects of various factors on the cryogenic mechanical and thermal properties.

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