Cryogenic performances of T700 and T800 carbon fibre–epoxy laminates

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Abstract. The temperature dependence of thermal expansion, thermal conductivity and mechanical properties of T700 carbon fibre (T700 CFs) /epoxy composite and T800 CF/epoxy composite were investigated. The mechanical and thermal properties of the unidirectional composite material laminates (0°/90°) at low temperature were studied. The results show that comparing the composite material T700 CFs with T800 CFs, the thermal expansion and thermal conductivity performances of T800 CFs (0°/90°) are all smaller than those of T700 CFs. Typically, the coefficient of thermal expansion (CTE) of T800 CFs in 0° is very low in the temperature range of 120-300K, which reaches as low as -0.4×10⁻⁶ K⁻¹. The value of thermal conductivity of this material at 0° is about 3.2 W.(m.K)⁻¹ at room temperature. Tensile and compression tests indicate that the tensile strength of T800 CFs in 0° direction at 77K reaches 2310 MPa, while the compressive strength is about 852 MPa. This composite material may possibly be exploited to design the critical components for practical applications such as hydrogen storage tanks.

1. Introduction
Composite materials have been extensively applied to the areas of aerospace, aircraft, sports and military industries because of their advantages over traditional materials, for example, a possibility to obtain a required combination of properties, which cannot be achieved for unfilled polymers [1]. Advanced composite materials have progressed from a laboratory curiosity to a production reality. It is known several carbon fibres, such as T300, T700, T800, have several advantages over the traditional metal structures in a wide temperature range. Meanwhile, the high specific strength, the high specific stiffness, and the very strong design ability of the composite material play an essential role in the weight reducing of aerospace structures. Commercial aircraft applications have ranged from small flight-control surfaces to more and more primary structures [2-5].

It is noteworthy, however, that owing to the extreme inertness of surface caused by the alignment of graphitic crystallites, high performance carbon fibres such as T700/T800 always failed to reach the expected properties in their reinforced composites [6]. Therefore, the ability to control the properties of composites over a wide range, by adjusting the reinforcing elements and the degree of filling, is the key for increased interest in composite materials. Modification of the interfacial behaviors between
carbon fibre and matrix is a feasible way to improve the mechanical properties of the high performance carbon fibre reinforced polymers [7-8].

In addition, optimization of the composite materials is very important when used in some severely loaded structures such as hydrogen storage tanks[9]. The behavior and performance of composite materials cannot be explained in terms of the specific properties of the constituents alone. The interface that exists between the fibres and the matrix is also a major component of the composite [10]. A good adhesion between the fibre and the matrix is a precondition for stress transfer and influences mechanical properties such as the interlaminar shear strength, fatigue resistance and impact toughness [11]. Therefore, many scientific efforts have been devoted to modify carbon fibres by a variety of methods such as gas-phase, liquid-phase and continuous anodic oxidation [12–15], and then to apply a very thin (usually on nanometer scale) coating of a prepolymer or resin to the modified carbon fibre surface for the purpose of improving the interfacial properties between the carbon fibres and matrix [16], and meanwhile to prevent the fibres from damage through the process of manufacture. Many investigations on the nature of the fibre/sizing and sizing/matrix interphases have proved that the nano-scale interface plays a dominant role in the interfacial adhesion between the carbon fibre and the resin matrix [17]. The functional groups of the sizing (interface) can react and/or interact with the matrix, which can give rise to strong adhesion between the fibre and the matrix.

Also, the thermal expansion due to the anharmonic behavior of atomic vibrations is a usual property exhibited by most materials but a most critical design parameter in advanced industrial applications. The mismatch of the thermal expansion of different components undergoing temperature change will cause thermal stress and then deformations that will lead to reliability problems. For hydrogen storage tanks, for example, some structures undergo thermal shock when temperature varies between high and cryogenic temperatures, resulting in residual stress and deformation [2, 18]. So the thermal expansion property of composite materials should be taken into consideration carefully.

Many investigations pay the attention on the properties of composites at room temperature. Seldom work, however, has been reported that the cryogenic performances of carbon fibre–epoxy composites. The purpose of this study is, thus, to fabricate carbon fibre composite materials and to investigate the mechanical and thermal properties of the unidirectional T700 CF/epoxy composites and T800 CF/epoxy composites (0º/90º) at low temperature.

2. Experiment

The material used was T700, T800 carbon fibre and the diglycidyl ester of aliphatic cyclo (DGEAC) type epoxy resin. This epoxy is one of the most widely used matrices for carbon fibre reinforced composite materials by virtue of its good impregnation and adhesion to carbon fibre. The DGEAC type epoxy resin was provided by Tianjin Jindong chemical factory (epoxy value, 0.85) and both T700 and T800 CFs were obtained from Toray Co., Japan. The resin casts and unidirectional composite laminates with 60% volume content of carbon fibres were cured at 80 ºC/2 h + 120ºC/2 h + 150 ºC/4 h[19].

The linear thermal expansion data (Δ L/L(300K)) were characterized using a dilatometer (L75 PT Vertical, LINSEIS, Germany) in the temperature range of 120 – 300 K in helium gas with a heating rate of 2 K/min. The thermal conductivity was measured by means of a heat and sink steady-state method, which is to establish a stationary temperature gradient, and supplying heat at one end of the sample while the other end is maintained at a constant temperature by measuring the temperature difference between a given distances. The temperature difference of the two ends of the sample was stabilized with an accuracy of better than 0.01 K. The thermal conductivity can be calculated by means of

\[
K = \frac{Q}{\dot{Q}} \cdot L \cdot S \cdot \Delta T
\]

Where \( K \) is the thermal conductivity, \( Q \), the power supplied, \( L \), the distance of sample, \( S \), the section of the sample and \( \Delta T \), the measured temperature difference. Tensile and compression tests were
conducted with a MTS SANS CMT 5000 model test machine (load capacity, 100 kN). The tensile and compression strength under monotonic loading were measured by stretching and compressing the specimen at a constant rate of 0.5 mm/min until failure.

It should be noted that the tensile strength (σ) can be determined as

\[ \sigma = \frac{P}{tw} \]  

(2)

Where \( P \) is the ultimate burst force recorded in Newton (N) and \( t \) and \( w \) are the thickness and width of the sample in millimeter (mm), respectively. More than six comparative specimens with dimensions of 20 mm×6 mm×2 mm were tested for each experiment to get an average value [20]. All the mechanical properties of the composites were determined according to ASTM 3039 test standard specifications [21].

3. Results and Discussion

3.1. Thermal expansion properties

The property of the composites may be influenced by the thermal expansion mismatch between fibre and matrix during a thermal excursion. So we studied the thermal expansion property of the carbon fibre composite material in a wide temperature range. Figure 1 shows temperature dependence of ΔL/L data of the T700/DGEAC and T800/ DGEAC. It is observed that all samples show a linear expansion as function of temperature at room temperature and the slope decreases gradually with decreasing temperature, which is similar to that observed in most materials. The ΔL/L curves are near-linear, and we calculated the CTE as shown in table 1. The results show the CTE of T800 CFs(0º /90º ) are all smaller than those of T700 CFs. Typically, the CTE of T800 CFs (0º ) is very low in the temperature range of 120-300K, which reaches as low as -0.4×10⁻⁶ K⁻¹. The reason for the wide differences of CTE between the composites in 0º and 90º direction is that in 0º direction, the CTE is dominated by the carbon fibres, while in 90º direction, the CTE is dominated by the resin.

![Figure 1.](image_url) The temperature dependence of the linear thermal expansions ΔL/L(300K) for the T700/ DGEAC and T800/ DGEAC composites.
3.2. Thermal conductivity

Thermal conductivity is basically the property of a material that indicates its ability to conduct heat. Low thermal conductivity is desirable for some applications such as hydrogen storage tanks in order to avoid heat loss. The temperature dependence of the T700 and T800 composites thermal conductivity are shown in Figure 2. The thermal conductivity increases monotonically with increasing temperature over the test temperature range. From the thermal conductivity curves, we can see that there is no very obvious difference between the T700-90º and T800-90º while the thermal conductivities of T700-0º are all larger than that of T800-0º more or less from 25 to 300K. The results show that comparing the composite materials in 0º and in 90º, the 0º are all larger than 90º just because of the higher thermal conductivity of the carbon fibres compared with the resins. And the gap between 0º and 90º become smaller from 300K to 20K, which is beneficial to the practical applications such as hydrogen storage tanks[22].

![Figure 2](image-url)

**Figure 2.** The temperature dependence of the thermal conductivity for the T700/ DGEAC and T800/ DGEAC composites.

3.3. Mechanical properties

In order to evaluate the mechanical properties of carbon fibre composite materials, tensile and compression tests were carried out at 77K and room temperature. The loading rate of the testing machine was 0.5mm / min. Load-displacement curves data were obtained from the tests and were used to determine the tensile and compressive strength. The load - displacement curves of the T700/ DGEAC and T800/ DGEAC laminates by the tensile test at 77K are shown as Fig. (3). Take the T800/ DGEAC in 0º for example, it can be recognized in the curve that the whole test curve of the laminate is changed as a line. As observed by the test, when the experimental load reached 25000N, the specimen started to make a cracking sound. As the load continued, the whole laminate was seriously

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**Table 3.** The coefficient of thermal expansion (CTE) for all samples

| Samples     | Direction(º) | CTE(10⁻⁶×K⁻¹) |
|-------------|--------------|---------------|
| T700/ DGEAC | 0            | 3.1           |
| T700/ DGEAC | 90           | 24.7          |
| T800/ DGEAC | 0            | -0.4          |
| T800/ DGEAC | 90           | 23.4          |
deformed, and then, completely broken. The load is decreased rapidly after reaching a maximum of 33090 N, and by then the laminate is completely damaged[23-24].

Figure 3. Tensile load - displacement curves of the T700/ DGEAC and T800/ DGEAC laminate.

From the stress-displacement curves we obtained the tensile and compressive strengths for the T700/ DGEAC and the T800/ DGEAC laminates at 77K and room temperature. The results of tensile and compression tests of the composite materials are shown in Fig. 4 and Fig. 5 respectively. We can see both the tensile strength and the compressive strength of the composites all increases monotonically with decreasing temperature. Typically, the value of tensile strength of the T800/ DGEAC in 0º direction at 77K is about 2310 MPa, while at the same condition, the tensile strength of the T700/ DGEAC is about 2293 MPa. The value of compressive strength of the T800/ DGEAC in 0º direction at 77K is about 852 MPa, while at the same condition, the compressive strength of the T700/ DGEAC is about 813 MPa. As is known from the tensile and compressive tests of the T700/ DGEAC and T800/ DGEAC laminates, under the condition of same physical dimension, the tensile and compressive properties of the T800/ DGEAC are slightly higher than those of the T700/ DGEAC. Considering the thermal properties of the materials, the whole properties of the former are apparently better than those of the latter. Also, just as the thermal properties, the differences of strengths between the composites in 0º and 90º direction are still very apparent.

Figure 4. The tensile and compressive strengths for the T700/ DGEAC and the T800/ DGEAC laminates in the 0º direction.
Figure 5. The tensile and compressive strengths for the T700/ DGEAC and the T800/ DGEAC laminates in the 90º direction.

4. Conclusions

1) The T700 and T800 carbon fibre/epoxy systems were fabricated and the cryogenic thermal expansion and tensile/compressive strengths of T700 and T800 carbon fibre–epoxy laminates were compared.

2) The CTE of the T700/ DGEAC and T800/ DGEAC carbon fibre/epoxy systems in 0º is smaller than that in 90º and in addition. The CTE of the T800/ DGEAC is very low in the temperature range of 120-300 K, which is \(-0.4 \times 10^{-6} \) K\(^{-1}\).

3) Under the same condition, the thermal and mechanical properties of the T800/ DGEAC are apparently better than those of the T700/ DGEAC. Typically, the value of tensile strength of the T800/ DGEAC at 77K is about 2310 MPa, while the thermal conductivity is 0.5 W/m.k.

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