M55J Carbon Fiber/Cyanate Ester Composites' Properties and Application

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Abstract

High modulus carbon fiber/cyanate ester composites are new materials increasingly used in aerospace structures. In this study, M55J/cyanate ester hot-melt prepregs and laminates are prepared and a M55J/cyanate ester telescope is produced. Laminates' moisture absorption, out-gassing, mechanical and thermal properties are measured and compared with T700/epoxy laminates. Telescope's coefficient of thermal expansion is measured.

Results show that M55J/cyanate ester laminates' total mass loss (TML) is as low as 0.07% by out-gassing measurement. Cyanate ester systems absorb significantly less moisture (one third) than epoxy systems. Coefficients of thermal expansion are near zero ($|\alpha_l| < 1 \times 10^{-6}/K$) in both longitudinal and transverse directions for M55J/cyanate ester laminates, as well as for the longitudinal direction of the telescope. All these data support the conclusion that M55J/cyanate ester system is an excellent candidate for dimensionally stable aerospace structures.

Introduction

Cyanate ester (CE) resin system is a relatively new generation thermosetting resin with some attractive physical, thermal, electrical and processing properties. The good dielectric properties and radar transparency make them suitable for radome applications. The low out-gassing, low moisture absorption and good dimensional stability make them the material of choice for satellite applications such as telescope tube and reflectors[1].

High modulus carbon fiber/CE composites with excellent dimensional stability are increasingly used for high precision aerospace applications as replacements for Al and Ti metal materials and traditional carbon fiber reinforced polymer composites (i.e. high strength carbon fiber/Epoxy)[2-7]. A comprehensive comparison between high strength carbon fiber/Epoxy composites and high modulus carbon fiber/CE composites is thus necessary to promote these new applications in aerospace industry.

In this study, M55J/cyanate ester hot-melt prepregs and laminates are prepared. Laminates' moisture absorption, out-gassing, mechanical and thermal properties are measured and compared with T700/epoxy laminates. A M55J/cyanate ester telescope with near zero coefficient of thermal expansion is produced.

Materials

- T700S high strength carbon fiber, produced by Toray Carbon Fibers America, INC.
- M55J high modulus carbon fiber, produced by Toray Carbon Fibers America, INC.
- 603 epoxy resin system, self-made.
- 701 cyanate ester resin system, self-made.
- T700/603 hot-melt prepregs, self-made.
- M55J/701 hot-melt prepregs, self-made.

Experimental procedure

Mechanical, thermal, water absorption and out-gassing properties of laminates are measured with test standard shown in table 1.

Table 1: Tests and standards

Test	Standard
Tensile property	ASTM D 3039
Compressive property	ASTM D 3410
Flexural property	GB/T1449-2005
ILSS	JC/T773-2010
Out-gassing	QJ 1558-1988
Water absorption	GB/T 1462-2005
Coefficient of thermal expansion	GJB 332A-2004
Thermal conductivity	GB/T 10295-2008

Unidirectional laminate

Table 2 shows comparison of mechanical properties of two composites laminates. M55J/701 system presents an obvious advantage on all the modulus-related properties.

For example, tensile modulus of M55J/701 is 303GPa, and that of T700/603 is 136GPa. This is mainly due to the contribution of the reinforced fibers.

Table 2: Tests and standards

	T700/epoxy	M55J/CE
Tensile strength/MPa	2310	1610
Tensile modulus/GPa	136	303
Compressive strength/MPa	1400	800
Compressive modulus/GPa	129	333
Flexual strength/MPa	1710	1040
Flexual modulus/GPa	116	233
ILSS/Mpa	102	62

Note: data are normalized to 60% fiber volume.

Water absorption

Water absorption of four materials (603 epoxy resin, 701 cyanate ester resin, T700/603 laminate and M55J/701 laminate) along with time is plotted in figure 1. It can be seen that epoxy resin has the greatest water absorption, which obtains 1.4% at 20 days and continue to increase rapidly. Cyanate ester resin has water absorption of 0.6% at 20 days and seems to have obtained equilibrium state. M55J/701 laminate has the least water absorption of less than 0.1%, being only on third of that of T700/epoxy laminate.

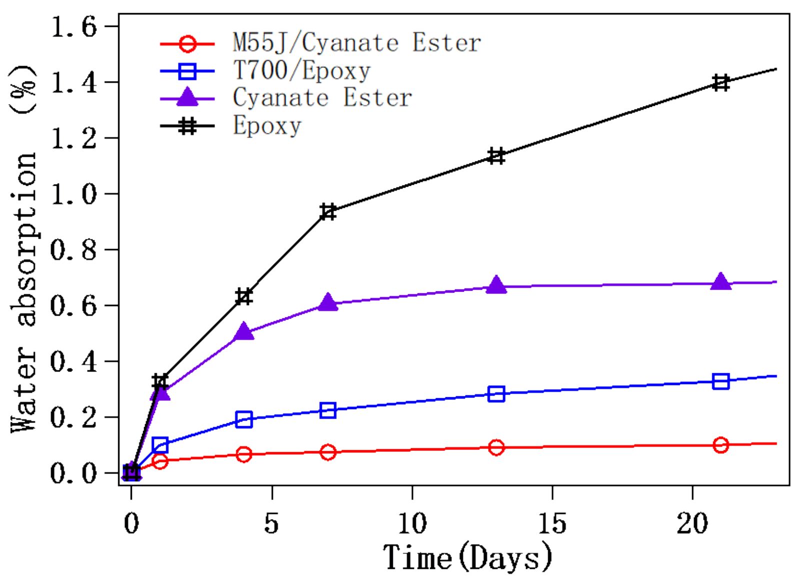

Figure 1: water absorption of resins and laminates

Out-gassing properties

Total Mass Loss (TML), Collected Volatile Condensable Materials (CVCM) and Water Vapor Regained (WVR) are measured for four material systems and results are shown in table 3. TML of CE resin is half that of epoxy resin and it’s the same for laminates. M55J/CE presents the best out-gassing property.

The ratios of laminates' TML and resins' TML are 33% and 27% for CE system and epoxy system respectively. These ratios are very close to the wt% of resin in the laminate (34%), suggesting that laminates' TML property is dominated by the matrix resin.

Table 3: Out-gassing properties

	TML /%	CVCM /%	WVR /%
CE	0.208	0.003	0.173
Epoxy	0.475	0.002	0.179
M55J/CE	0.069	0.003	0.051
T700/epoxy	0.129	0.003	0.055

Thermal conductivity

Thermal conductivity of two laminates are measured in the through-thickness direction. M55J/CE laminate has a value about 1 $Wm^{-1}K^{-1}$ from 50°C to 200°C, which is about 50% higher than that of T700/Epoxy laminate.

Table 4: Thermal conductivity

T /℃	T700/Epoxy /$Wm^{-1}K^{-1}$	M55J/CE /$Wm^{-1}K^{-1}$
50℃	0.63	1.01
100℃	0.68	1.04
150℃	0.73	1.06
200℃	0.78	1.06

Coefficient of thermal expansion (CTE) for unidirectional laminates

CTE of two laminates are measured in both 0° and 90° directions and values are compared in table 5. M55J/CE presents an evident negative value in the fiber direction. This is beneficial for minimizing the CTE of multi-directional laminate and products by design of layup orientations.

Table 5: CTE properties

CTE ($\times 10^{-6}$/℃)				
T /℃	M55J/CE		T700/Epoxy	
	0°	90°	0°	90°
RT～100	-0.88	35.7	0.14	32.56
RT～150	-0.71	35.55	0.14	34.02
RT～200	-0.64	39.42	-0.11	32.09

Design of layup of telescope tube

Numerical simulation of thermal expansion of M55J/CE multi-directional laminate is realized by ANSYS. The objective is to minimize the thermal expansion in the longitudinal direction in order to minimize the effect of temperature gradients on the stability of the focus.

The input parameters are modulus, Poisson ratio, CTE of unidirectional laminates in 0° and 90° directions. Two layup options are simulated:

1) [+45/-45/0/90/0]s

2) [+45/-45/0/90]s

Numerical simulation model and results are shown in figure 2.

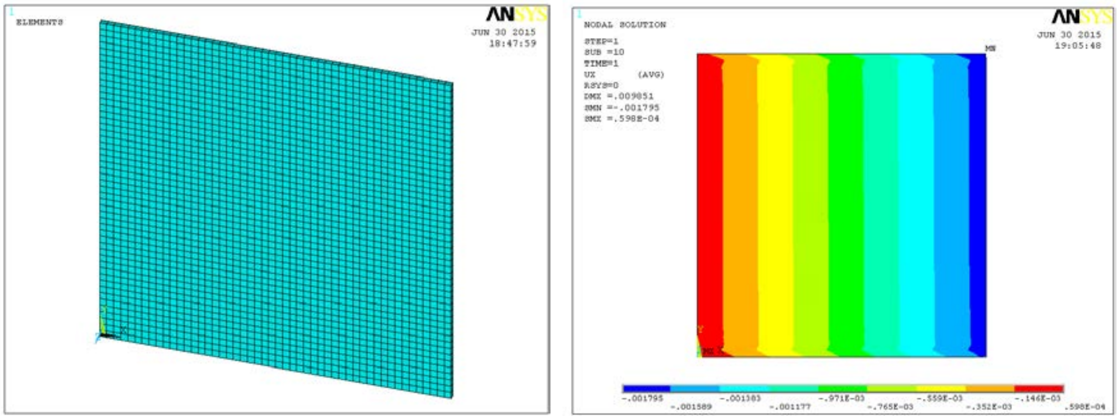

Figure 2: Numerical simulation of thermal expansion of M55J/CE multi-directional laminate by ANSYS. (a) Meshing; (b) Deformation.

The value of CET is obtained from simulation results and calculated by equation 1.

$$CET = \frac{strain}{\Delta T} \qquad \text{eq.1}$$

Results of CET are shown in table 6. It can be seen that $[+45/-45/0/90/0]_S$ layup corresponds to a minimum of CTE, and this layup is thus applied to the following multi-directional laminate and telescope tube product.

Table 6: CTE obtained from ANSYS simulation

layup	Longitudinal CTE $/\times10^{-6}$	Transverse CTE $/\times10^{-6}$
$[+45/-45/0/90/0]_s$	-0.18	0.76
$[+45/-45/90/0]_s$	0.20	0.20

CTE for layup multi-directional laminates specimen

M55J/CE multi-directional laminates are prepared with $[+45/-45/0/90/0]_s$ layup according to above simulation and design results. Specimens are prepared for both longitudinal and transverse directions.

Results are shown in table 7. It can be seen that experimental results are extremely close to that of simulation. For example, simulation predicts a CTE value of -0.18×10^{-6}/K in the longitudinal direction and experiment gives a value of -0.17×10^{-6} /K in the range of room temperature to 50℃. Besides, the CTE value in the transverse direction is also near zero (＜1×10^{-6}/K).

Table 7: CTE measurement of M55J/CE $[+45/-45/0/90/0]_S$ layup

T /℃	Longitudinal CTE $/\times10^{-6}$	Transverse CTE $/\times10^{-6}$
RT～50	-0.17	0.53
RT～100	-0.31	0.67
RT～150	-0.38	0.81
RT～200	-0.60	0.82

Application on telescope tube

A M55J/CE telescope tube is made with $[+45/-45/0/90/0]_S$ layup with the following dimensional parameters:

- Length: 557mm
- Diameter:140mm
- Thickness: 1.5mm

The processability of the M55J/CE hot-melt prepreg is good and the application on telescope tube is proved to be successful.

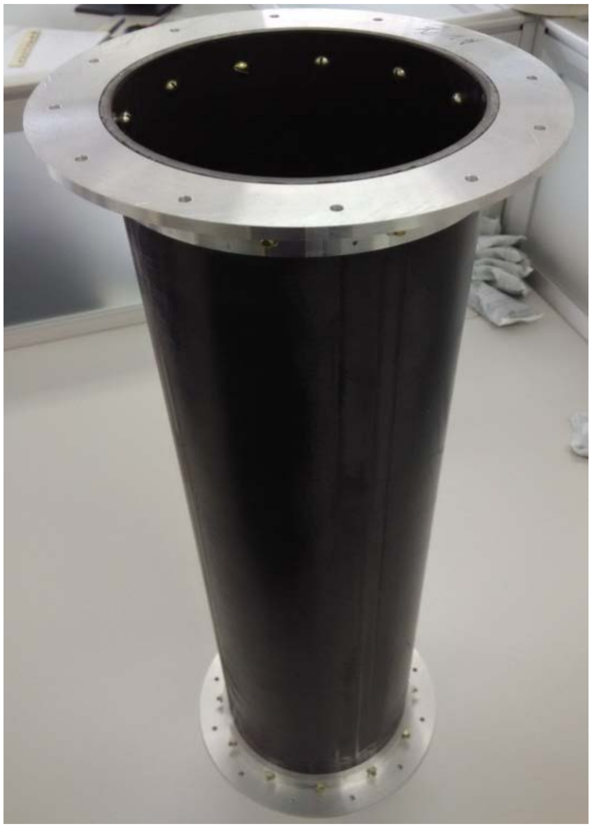

Figure 3: M55J/CE telescope tube

Conclusions and Recommendations

M55J/CE composite has several advantages compared to T700/epoxy composite and is proved to be an excellent candidate for dimensionally stable aerospace structures.

1) M55J/CE laminate has excellent tensile modulus of 303GPa.
2) Cyanate ester system has better out-gassing and water absorption properties than epoxy system.
3) Coefficients of thermal expansion are near zero ($|CTE| < 1 \times 10^{-6}$/K) in both longitudinal and transverse directions for M55J/cyanate ester $[+45/-45/0/90/0]_S$ layup laminate.

Acknowledgements

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