Thermal Cycling of Thin and Thick Ply Composites

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Abstract

An experimental study was conducted to determine the effects of ply thickness in composite laminates on thermally induced cracking and changes in the coefficient of thermal expansion (CTE). After a few thermal cycles, laminates with thick-plies cracked, resulting in large changes in CTE. CTEs of the thin-ply laminates were unaffected by microcracking during the first 500 thermal cycles, whereas, the CTEs of the thick-ply laminates changed significantly. After about 1500 cycles, microdamage had also reduced the CTE of the thin-ply laminates to a value of about half of their initial value.

Introduction

Resin matrix composite materials have evolved as a primary candidate material in the design and fabrication of dimensionally stable spacecraft because of very low coefficients of thermal expansion (CTE) and high specific stiffness. The standard 0.127 mm prepreg used to fabricate composite laminates is being replaced by thinner, 0.025 mm to 0.076 mm, prepreg in many material designs for additional weight savings (Kulick 1992 and Kilpatrich and Girard 1992). The comparative properties and performance of laminates fabricated from the thinner

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prepreg and those fabricated with the standard thickness prepreg is a fundamental question that must be addressed as materials are replaced.

The properties and response to mechanical loads of composite laminates fabricated with different ply thicknesses have been investigated in composite laminate scaling studies (Kellas and Morton 1992, and O'Brien and Sulpekar 1992) and other studies (Crossman and Wang 1982). Results from these studies have shown that laminates with the same materials and configuration but fabricated with different ply thicknesses do not have the same mechanical properties. While the stiffnesses are the same for the two materials, the transverse strengths are significantly different. This difference has been attributed to both a material volume effect (O'Brien and Sulpekar 1992) and a ply constraint effect (Kellas et al. 1993).

Crossman and Wang 1982, have also established that damage induced by mechanical fatigue is dependent upon laminate ply thickness. Manders and Maas 1990, showed similar results for high modulus fibers subjected to limited thermal fatigue. Results from both studies showed that laminates fabricated with thin plies had more microcracks than similar laminates with thicker plies. The differences in the induced damage has been attributed to differences in inter-ply constraints, where the constraint was highest within laminates with thinner plies.

The effects of laminate ply thickness on thermally induced microdamage and the resulting changes in laminate properties has not been well documented. The objective of the present study was to investigate the effects of ply thickness on thermally induced microdamage and the resulting changes in the CTE after a large number of thermal cycles. A high modulus continuous graphite fiber composite material, representative of a spacecraft material, was used in this study.

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Material, Specimens, and Test Procedures

All of the laminate panels were fabricated by Advanced Composite Products using P75/ERL 1962 composite prepreg from Amoco Performance Products, Inc. The ERL

1962 epoxy matrix is a toughened epoxy formulated for space applications with lower moisture absorption than standard epoxy systems and has been used in spacecraft design. The P75 fiber is a high modulus pitch base graphite fiber made by Amoco and is used in many spacecraft designs. All of the laminates had a layup of $[(0/90)_n]_s$. Laminates were fabricated using 0.127 mm plies with n=2 and using 0.025 mm plies with n=10 and n=2. This resulted in laminates with the same total thickness (n=2 and n=10), but with different ply thicknesses, and laminates with the same total number of plies (n=2). The laminates are shown schematically in Fig. 1. The percent fiber volume content of the laminates made with the thick- and thin-plies were about 53% and 58%, respectively.

Specimens, approximately 2.54 cm x 7.62 cm were cut from each laminate with the 0° fiber aligned with the 7.62 cm direction. One edge of each specimen was polished, so that microcracks induced by thermal cycling could be observed. After each specimen was dried to constant weight in a warm vacuum, they were thermally cycled between -156°C and 121°C up to 1500 times.

The thermal cycling was performed in an apparatus consisting of a hot chamber heated with electric resistance heaters and an adjacent cold chamber cooled with liquid nitrogen. A typical cycle between -156°C to 121°C as measured on a specimen instrumented with a thermocouple was about 15 minutes. Microcrack densities, number/cm, were determined by counting the microcracks over the middle 2.5 centimeters along the polished edge using an optical microscope at a magnification of 400X. A microcrack was counted if it extended at least half way across the ply thickness. Only the cracks in the middle two 90° plies were counted and recorded.

Thermal expansion measurements were made in the fiber direction only with a Fizeau-type laser interferometric dilatometer specifically developed for measuring small thermal strains in composites (Tompkins et al. 1986). This dilatometer measures the changes in length of each specimen relative to the change in length of a reference material (The National Institute of Standards and Technology, 739 fused silica). The strain resolution of this system is approximately 1×10^{-6}.

Results and Discussion

Microcrack densities of the specimens from the two thin-ply laminates and the thick-ply laminate are shown in Fig. 2 and Table I. The microcrack growth was very
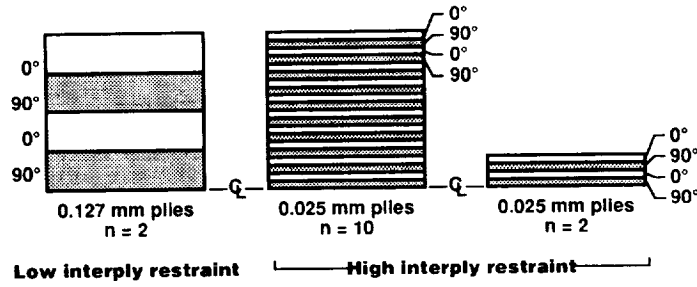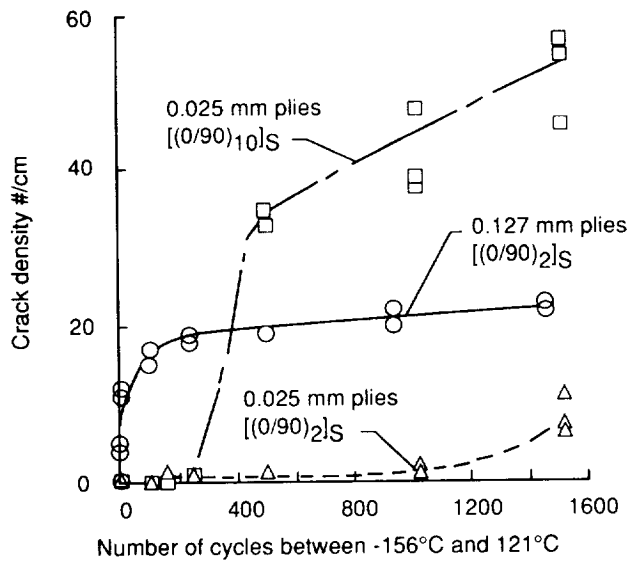
Figure 1 - Schematic diagram of [(0/90)n]s laminates.

Figure 2 - Microcrack density induced in P75/ERL 1962
[(0/90)n]s laminates during thermal cycling.

Table I - Specimen crack densities in the middle 90° plies after thermal cycling between -156°C and 121°C.

Layup	Ply thick, mm	Microcrack density, number/cm											
		Number of cycles between -156°C and 121°C											
		0	1	10	100	150	238	250	500	938	1021	1459	1521
[(0/90)$_2$]$_s$	0.127	0	4	11	17	---	18	---	19	22	---	23	---
		0	4	12	17	---	19	---	19	20	---	22	---
		0	5	11	15	---	18	---	19	22	---	23	---
[(0/90)$_{10}$]$_s$	0.025	0	0	0	0	0	---	1	33	---	39	---	57
		0	0	0	0	0	---	1	33	---	38	---	46
		0	0	0	0	0	---	1	35	---	48	---	55
[(0/90)$_2$]$_s$	0.025	0	0	0	0	1	---	1	1	---	2	---	7
		0	0	0	0	1	---	1	1	---	1	---	11
		0	0	0	0	1	---	1	1	---	1	---	6

Table II - Coefficient of thermal expansion of P75/ERL 1962 [(0/90)$_n$]$_s$ laminates before and after thermal cycling.

Layup	Ply thick, mm	Coefficient of thermal expansion, ppm/°C							
		Number of cycles between -156°C and 121°C							
		0	1	100	150	250	500	1459	1521
[(0/90)$_2$]$_s$	0.127	0.234	---	-0.137	---	-0.344	-0.351	-0.547	---
		0.266	---	-0.162	---	-0.279	-0.302	-0.486	---
		0.097	---	-0.202	---	-0.378	-0.385	-0.560	---
[(0/90)$_{10}$]$_s$	0.025	0.432	---	---	---	0.450	0.376	---	0.202
		0.358	---	---	---	0.419	0.360	---	0.099
		---	---	---	---	0.409	0.407	---	0.189
[(0/90)$_2$]$_s$	0.025	0.266	0.360	---	0.392	0.346	0.346	---	0.189
		0.353	0.342	---	0.275	0.261	0.223	---	0.187
		0.358	0.342	---	0.374	0.371	0.382	---	0.236

different for each of the laminates. The thick-ply
laminate began cracking with the first cycle, as was
expected. However, the thin-ply, n=10 laminate did not
start cracking until about 250 cycles after which the
crack density increased very rapidly. The thin-ply, n=2
laminate had a very low crack density up to about 1000
cycles, after which the crack rate increased. While the
thick-ply laminate appeared to reach a crack equilibrium
density after about 250 cycles, the thin-ply, n=10
laminate, exhibited a high crack growth rate even after
1500 cycles. The microcrack density of this laminate,
after 1500 cycles, was more than twice the density of the
thick-ply laminate (about 20 cracks/cm). The thin-ply,
n=2 laminate reached a density of only about 8 cracks/cm
after 1500 cycles. The difference in the cracking in the
two thin-ply laminates is not understood and is under
investigation.

The large differences in crack densities in the thin-
and thick-ply laminates of equal total thickness are
attributed to the fact that the thin plies are more
constrained by adjacent plies than the thick plies. This
constraint restricts the straining of the plies which
resulted in a high stress required for cracking and
delayed crack initiation. Also, the constraint does not
allow the stress relief by cracking to extend far from the
crack, as in the thicker plies, thus resulting in a higher
crack density. The results in Fig. 2 are consistent with
the trends predicted by an approximate analysis by McManus
et al. 1993. This analysis, based on shear lag stress
approximations and an energy-based fracture criteria,
predicts crack density and property change as a function
of the number of thermal cycles. These data and analysis
clearly show that microcrack growth and equilibrium crack
density are very dependent upon both the ply thickness and
total number of plies.

The effects of microcracking on laminate thermal
expansion and CTE are shown in Figs. 3 and 4, respectively
and Table II. As the microcrack density in the thick-ply
laminate increased, the thermal strain, Fig. 3, and the
CTE, Fig. 4, changed significantly. As the crack density
increases, the laminate thermal expansion, Fig. 3, becomes
dominated by the 0° plies of the laminate. Likewise, the
CTE changes from a positive value to a negative value and
approaches the longitudinal lamina value of -0.956 ppm/°C.
The CTE's of both of the thin-ply laminates, however, were
not significantly changed after 500 cycles even though the
crack density in the thin-ply, n=10 laminate was very
large (about 35 cracks/cm). The near constant CTEs were
attributed to the constraint on the cracked plies imposed
by the adjacent plies. Interply constraint was also

present in the thick-ply laminate, however, that constraint was not large enough to cancel the effects of the cracking. As thermal cycling continues, the crack density increases and the effects of the constraining adjacent plies is reduced. This results in a decrease in the CTEs in all of the laminates. After about 1500 cycles, both of the thin-ply laminates approach about the same value, 0.18 ppm/°C, half of the initial value. The CTE of the thick-ply laminate also decreases but to an average value of -0.531 ppm/°C, down from the value of -0.346 ppm/°C at 500 cycles and the initial value of 0.2 ppm/°C. The analysis by McManus et al. 1993 agrees qualitatively with the data in Fig. 4, that shows that the crack density in the thin-ply laminates, although very large, has a much smaller effect on the laminate CTE than the cracks in the thick-ply laminate.

Continued cycling may induce additional cracking in all of the laminates as is indicated by Fig. 3. Fig. 5 shows CTE of each of the laminates as a function of the microcrack density. These data seem to indicate that once microcracks begin to accumulate, the initial rates of change of CTE with microcracking are about the same for the thin- and thick-ply laminates with the same number of plies (n=2). The rate of change of CTE with microcraking for the thin-ply laminate with n=10 is very small up to a crack density of about 35-40 cracks/cm, after which the rate begins to increase.

The data show that even though no cracks are formed in thin-ply laminates after a few thermal cycles, cracks may form and ultimately reach a density much larger than thick-ply laminates. The CTEs of the thin-ply laminates were unaffected by microcracking during the first 500 thermal cycles, whereas, the CTEs of the thick-ply laminates changed significantly. After about 1500 cycles, microdamage had also reduced the CTE of the thin-ply laminates to a value of about half of their initial value.

Concluding Remarks

A graphite-epoxy composite material, in thin (0.025 mm) and thick (0.127 mm) prepregs, was used to make cross-ply laminates, [(0/90)$_n$]$_s$, with equal total thickness (n=2, n=10) and cross-ply laminates with the same total number of plies (n=2). Specimens of each laminate configuration were cycled up to 1500 times between -156°C and 121°C. Thermally induced microdamage was assessed as a function of the number of cycles as was the change in the CTE. The results showed that laminates fabricated with thin-plies microcracked at significantly different rates and reached
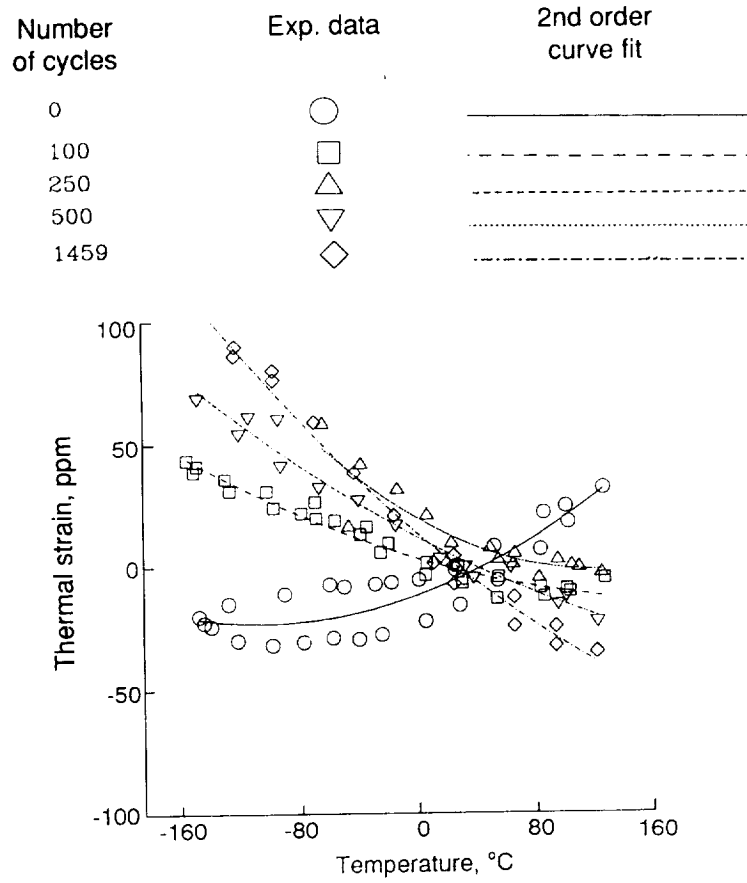
Figure 3 - Effects of continual thermal cycling on the thermal expansion of 75/ERL 1962 [(0/90)n]s laminates, 0.127 mm plies. Specimen cycled between -156°C and 121°C.
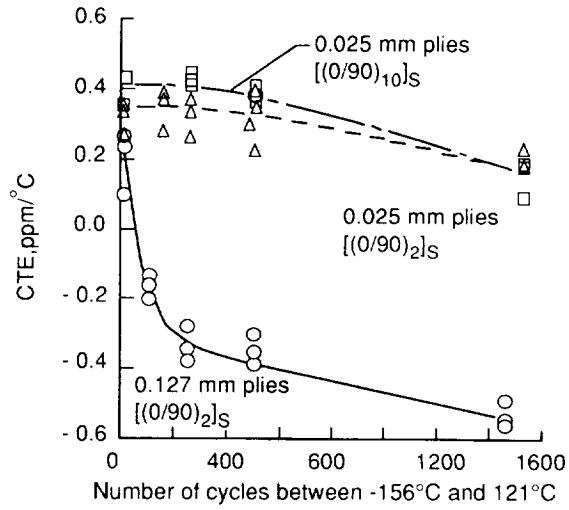
Figure 4 - Residual CTE for P75/ERL 1962 [(0/90)n]s laminates.
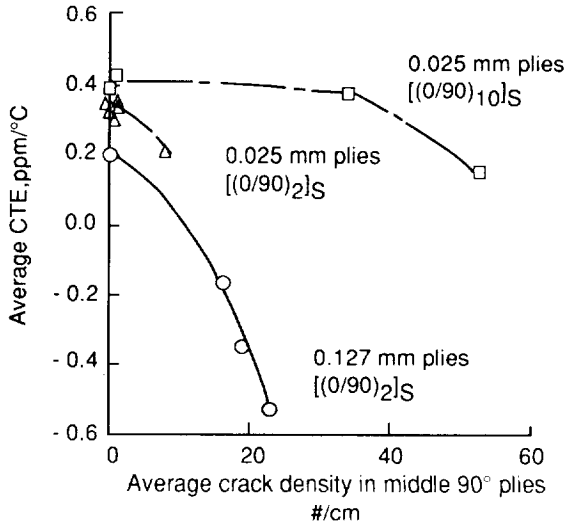

Figure 5 - Effects of microcracking of CTE of P75/ERL 1962 [(0/90)n]s laminates.

significantly different equilibrium crack densities than the laminate fabricated with thick-ply and n=2. These differences are attributed primarily to differences in interply constraints. CTEs of the thin-ply laminates were unaffected by microcracking during the first 500 thermal cycles, whereas, the thick-ply laminates changed significantly. After about 1500 cycles, microdamage had also reduced the CTE of the thin-ply laminates to a value of about half of their initial values.

Appendix 1. References

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