JOURNAL OF MATERIALS SCIENCE 28 (1993) 19–34

Temperature dependence of the tensile behaviour of aramid/aluminium laminates

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Aramid/aluminium laminates (ARALL® laminates) are a family of new hybrid composites made of alternating layers of thin aluminium alloy sheets with plies of epoxy adhesive prepreg containing unidirectional aramid fibres. The effect of elevated and cryogenic temperatures on these materials is critical to aerospace applications. ARALL 1, 2, 3, and 4 laminates have been tested in tension at temperatures ranging from −300F–400 °F (−184–204 °C) and at room temperature after exposure. This paper summarizes how tensile properties depend on temperature for these four ARALL laminates under the conditions described. At cryogenic temperatures, no degradation of ultimate tensile strengths, tensile yield strengths and moduli were found for either the longitudinal or transverse directions for ARALL 1–4 laminates. Furthermore, the mechanical properties remained the same or increased slightly as the temperature decreased. Longitudinal and transverse ultimate tensile strengths, tensile yield strengths, and moduli of ARALL 1–3 laminates at room temperature remain nearly constant after the laminates were exposed for 1, 10 and 100 h to temperatures up to 250 °F (121 °C), and up to 350 °F (177 °C) for ARALL 4 laminates. However, these properties determined at the elevated temperatures after 1, 10 and 100 h exposure showed a tendency to decrease with increasing temperature. The properties of ARALL laminates are much better in the longitudinal fibre direction than those of conventional monolithic aluminium alloys. Typical failure modes of the test specimens in the high-temperature range were examined using a scanning electron microscope. The discussions are also described in the paper.

1. Introduction

ARALL® laminates* are a new family of structural composites that offer good promise of weight savings for fatigue and fracture critical applications [1–6]. These hybrid aluminium laminates consist of multiple layers of anodized aluminium sheet, bonded by alternate layers of adhesive, impregnated with unidirectional aramid fibres. A schematic representation is shown in Fig. 1. The concept of ARALL laminates was originated at the Delft University of Technology in the 1970s [1–6], and is now commercialized by Alcoa [7–10].

Results reported previously [1–7] show that ARALL laminates have outstanding fatigue properties in comparison to conventional monolithic aluminium materials. Under cyclic loading, fatigue cracking in the aluminium plies is restricted or arrested by the strong aramid fibres that bridge the cracks and absorb the load. In addition, ARALL laminates have significantly higher static properties in the fibre direction than conventional high-strength aluminium alloys, 7075-T6 and 2024-T3, and are about 15% less dense.

These excellent material characteristics make them a prime candidate for application in tension-dominated, fatigue- and fracture-critical aircraft structures, such as fuselages and lower wing and tail skins. Attendant design/trade studies on these components have identified the potential for weight savings of more than 30% over standard aerospace metals [7]. Also, the stability of mechanical properties over the potential operating temperatures is very important for structural applications of composite materials. This stable thermal capability of the materials is absolutely needed in aerospace applications.

This paper summarizes the characterization of the tensile properties of ARALL laminates under various thermal conditions, including exposure to various elevated and cryogenic temperatures.

2. Experimental procedure

2.1. Materials and specimens

ARALL laminates can have different combinations by varying aluminium sheet alloys, fibre–resin systems, stacking sequences, fibre orientations, and surface preparation techniques. The four ARALL laminates used for this investigation, ARALL 1–4, are commercially available. Table I lists these four ARALL laminates product forms. ARALL 1 laminates are 7475-T61 based, have 0.4% nominal stretch, and are intended

* Registered trademark for Alcoa.

TABLE I ARALL laminates aerospace product line

ARALL type	Description	Characteristic	Introduction	AMS specs.	MIL-HDBK-5 allowables
1	7475-T61 250 °F (121 °C) aramid prepeg, unidirectional, 0.4% stretched.	Superior fatigue Highest strength	1984	1988	1993
2	2024-T3 250 °F (121 °C) aramid prepeg, unidirectional, no stretch	Excellent fatigue Increased formability Damage tolerance	1984	1988	1992
3	7475-T761 250 °F (121 °C) aramid prepeg, unidirectional, 0.4% stretched	Superior fatigue Controlled toughness Exfoliation resistance High strength	1987	1989	1991
4	2024-T8 350 °F (177 °C) aramid prepeg, unidirectional, no stretch	Excellent fatigue Elevated temperature	1988	1989	1993
5, 6	Various aluminium, fibre and cross-ply combinations	Tailored properties	1988 and beyond	1991 and beyond	1993 and beyond

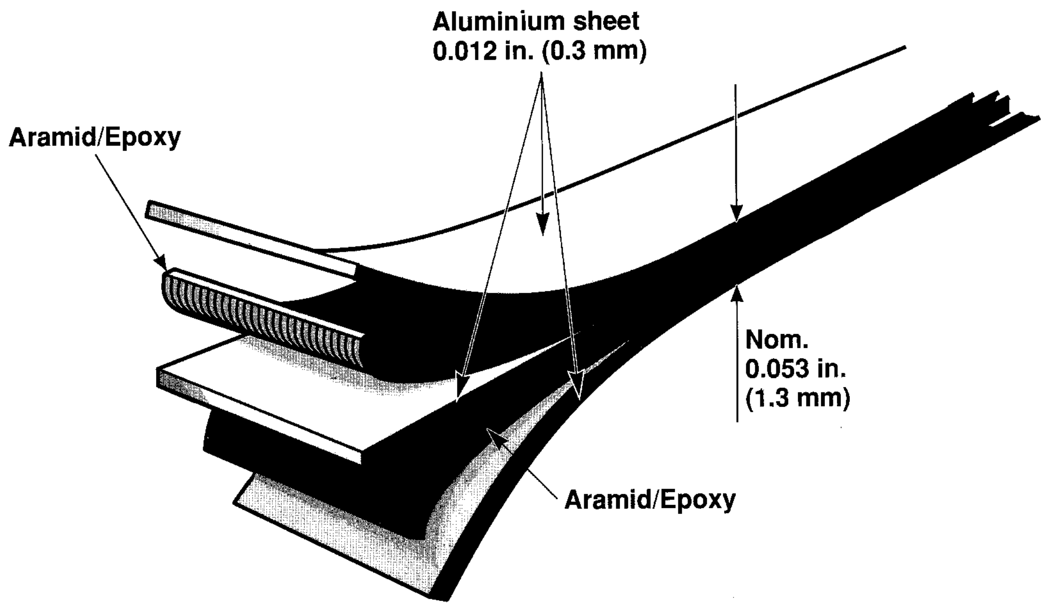


Figure 1 Alcoa ARALL laminates: schematic illustration of standard 3/2 lay-up.

for high fatigue-loaded structures which have high compressive loadings. ARALL 2 laminates are 2024-T3 based, have good ductility and toughness, and are designed for applications requiring damage tolerance and formability. This material is intended for fatigue applications with low compressive loadings. ARALL 3 laminates are 7475-T761 based and are intended for improved fracture toughness, corrosion and formability. ARALL 1–3 laminates use a 250 °F (121 °C) cure resin (3M AF-163-2U) prepreg with a recommended continuous service temperature of 200 °F (~ 93 °C). This thermoset adhesive system is impregnated with unidirectional aramid fibres in a fibre/resin (50/50) weight ratio. The fibres are oriented parallel to the aluminium sheet rolling direction. ARALL 4 laminates are 2024-T8 based and employ a special resin (3M AF-191), 350 °F (177 °C) cure resin prepreg (containing the same aramid fibres) with a recommended continuous service temperature of 325 °F (163 °C), and are intended for high-temperature applications.

The failure modes of fractured specimens were examined using a scanning electron microscope for distinguishing the fracture topography through the influence of temperatures.

The number and thickness of plies of ARALL laminates can be varied. In this research, the 3/2 configurations of ARALL laminates in both longitudinal and transverse directions were studied. The fibres that are parallel to the tensile direction are designed as L. The fibres that are perpendicular to the tensile direction are designed as LT. The 3/2 ARALL laminates consist of three layers of aluminium alloy sheet (0.012

TABLE II Tensile properties[a] of 3/2 ARALL 1 laminates in the longitudinal and transverse directions after short term exposure to cryogenic temperature

Temperature (°F (° C))	Longitudinal			Transverse		
	UTS (10^3 p.s.i. (MPa))	TYS (10^3 p.s.i. (MPa))	Modulus[b] (10^6 p.s.i. (GPa))	UTS (10^3 p.s.i. (MPa))	TYS (10^3 p.s.i. (MPa))	Modulus[b] (10^6 p.s.i. (GPa))
75 (24)	121 (834)	94 (648)	9.9 (68)	58 (400)	50 (345)	7.0 (48)
0 (− 18)	122 (841)	97 (669)	10.2 (70)	59 (407)	52 (359)	7.3 (50)
− 65 (− 54)	122 (841)	98 (676)	10.6 (73)	61 (421)	53 (365)	7.4 (51)
− 100 (− 73)	126 (869)	99 (683)	11.6 (80)	60 (414)	54 (372)	7.8 (54)
− 150 (− 101)	122 (841)	99 (683)	10.6 (73)	62 (428)	56 (386)	7.6 (52)
− 200 (− 129)	127 (876)	101 (696)	11.6 (80)	64 (441)	56 (386)	7.8 (54)
− 250 (− 157)	128 (883)	100 (690)	10.7 (74)	64 (441)	57 (393)	8.0 (55)
− 300 (− 184)	128 (883)	105 (724)	10.4 (72)	67 (462)	59 (409)	7.8 (54)

[a] Data reported are mean values from at least two tests.
[b] Approximate modulus.

TABLE III Tensile properties[a] of 3/2 ARALL 2 laminates in the longitudinal and transverse directions after short term exposure to cryogenic temperature

Temperature (°F (°C))	Longitudinal			Transverse		
	UTS (10^3 p.s.i. (MPa))	TYS (10^3 p.s.i. (MPa))	Modulus[b] (10^6 p.s.i. (GPa))	UTS (10^3 p.s.i. (MPa))	TYS (10^3 p.s.i. (MPa))	Modulus[b] (10^6 p.s.i. (GPa))
75 (24)	106 (731)	55 (379)	9.7 (67)	47 (324)	33 (228)	7.2 (50)
0 (− 18)	106 (731)	53 (365)	10.1 (70)	48 (331)	35 (241)	7.5 (52)
− 65 (− 54)	106 (731)	53 (365)	10.2 (70)	48 (331)	36 (248)	7.4 (51)
− 100 (− 73)	107 (738)	54 (372)	10.2 (70)	49 (338)	36 (248)	8.2 (57)
− 150 (− 101)	107 (738)	54 (372)	10.4 (72)	49 (338)	40 (276)	8.0 (55)
− 200 (− 129)	104 (717)	53 (365)	10.6 (73)	51 (352)	40 (276)	8.4 (58)
− 250 (− 157)	105 (724)	55 (379)	10.9 (75)	51 (352)	41 (283)	8.2 (57)
− 300 (− 184)	108 (745)	56 (386)	11.2 (77)	55 (379)	44 (303)	8.4 (58)

[a] Data reported are mean values from at least two tests.
[b] Approximate modulus.

in thick or 0.3 mm thick) and two layers of aramid/epoxy adhesive prepreg (0.0085 in thick or 0.22 mm thick). Specimens were tabless and straight-sided and were fabricated in accordance with ASTM D-3039.

2.2. Test procedures

For the short-term exposure to cryogenic temperatures, the specimens were first installed into the test machine taken to the desired temperature, held 5 min and then tested.

For the long-term exposure to cryogenic and elevated temperatures, the following three conditions were studied: (1) properties at room temperature without prior temperature exposure, (2) properties at temperature after 1, 10 and 100 h exposure to temperature, and (3) properties at temperature (− 65–400 °F or − 54–204 °C) after 1, 10 and 100 h exposure to temperature. Specimens exposed to elevated temperatures were heated for the desired time and temperature using an environmental chamber. For those specimens to be tested at room temperature, the tests were performed within 1.8–2.0 h from the time they were removed from the environmental chamber. The specimens to be tested at elevated temperatures were reheated to the exposure temperature and tested immediately. Specimens exposed to cryogenic temperatures were cooled in the same environmental chamber but having a vaporized liquid nitrogen atmosphere. The specimens to be tested at room temperature were tested 1 day after removal from the environmental chamber. However, the specimens to be tested at cryogenic temperatures were recooled to the exposure temperature and tested immediately. All tensile tests were conducted at temperatures ranging from − 65–400 °F (− 54–204 °C) at a strain rate (assumed ratio of crosshead speed to gauge length) of 0.01 min^{-1}.

At least two replicates of each of these conditions were measured for ultimate tensile strength (UTS), tensile yield strength (TYS), and tensile modulus. All the tensile moduli reported in the text are approximate moduli.

3. Results and discussion

3.1. Short-term exposure to cryogenic temperatures

Tensile tests of ARALL 1–3 laminates in both the longitudinal (L) and transverse (LT) directions were conducted with short-term exposure to cryogenic temperatures. Data are summarized in Tables II–IV and

TABLE IV Tensile properties[a] of 3/2 ARALL 3 laminates in the longitudinal and transverse directions after short term exposure to cryogenic temperature

Temperature	Longitudinal			Transverse		
(°F (°C))	UTS (10^3 p.s.i. (MPa))	TYS (10^3 p.s.i. (MPa))	Modulus[b] (10^6 p.s.i. (GPa))	UTS (10^3 p.s.i. (MPa))	TYS (10^3 p.s.i. (MPa))	Modulus[b] (10^6 p.s.i. (GPa))
75 (24)	121 (834)	89 (614)	9.7 (67)	55 (379)	48 (331)	7.1 (49)
0 (− 18)	122 (841)	89 (614)	10.6 (73)	57 (393)	51 (352)	7.7 (53)
− 65 (− 54)	119 (820)	89 (614)	11.5 (79)	58 (400)	53 (365)	7.5 (52)
− 100 (− 73)	121 (834)	91 (627)	10.3 (71)	59 (407)	55 (379)	7.4 (51)
− 150 (− 101)	119 (820)	93 (641)	11.2 (77)	61 (421)	57 (393)	7.6 (52)
− 200 (− 129)	121 (834)	93 (641)	10.2 (70)	62 (428)	56 (386)	8.3 (57)
− 250 (− 157)	123 (848)	94 (648)	10.6 (73)	62 (434)	57 (393)	8.8 (61)
− 300 (− 184)	122 (841)	94 (648)	11.2 (77)	65 (448)	58 (400)	9.0 (62)

[a] Data reported are mean values from at least two tests.
[b] Approximate modulus.

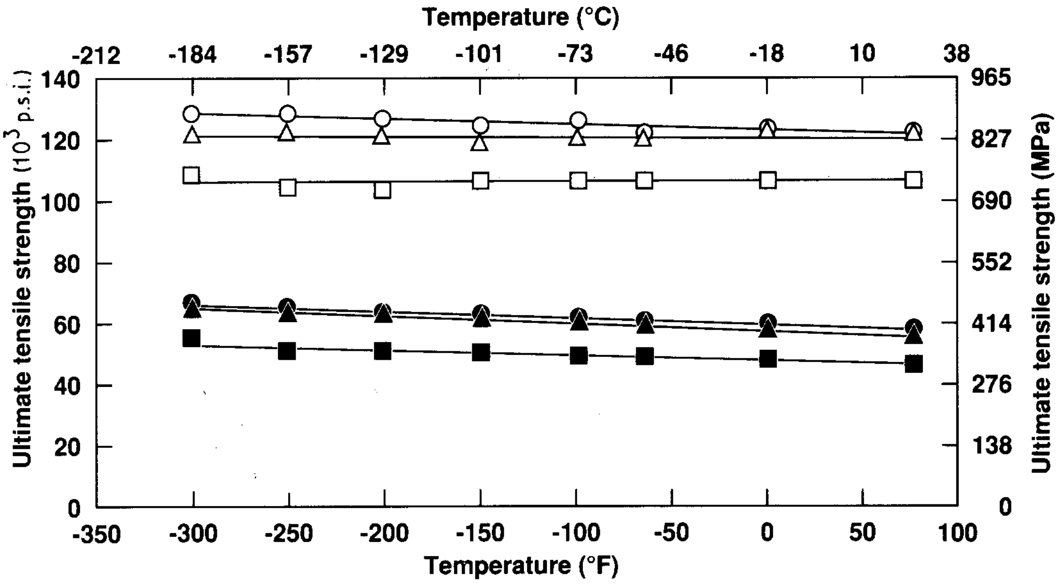


Figure 2 Ultimate tensile strength versus cryogenic temperature for various ARALL laminates. (○, □, △) L, (●, ■, ▲) LT. (○, ●) ARRAL 1, (□, ■) ARRAL 2, (△, ▲) ARRAL 3.

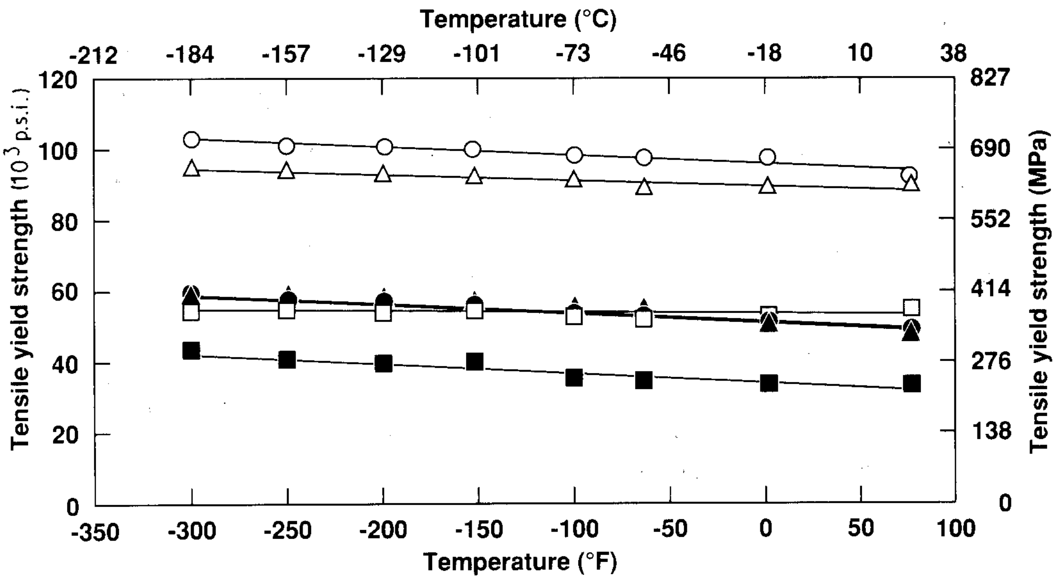


Figure 3 Tensile yield strength versus cryogenic temperature for various ARALL laminates. For key, see Fig. 2.

are shown in Figs 2–4. Results show that the ultimate tensile strengths, tensile yield strengths, and moduli all remain the same or increase slightly as the temperature decreases. These increases are about 3%–8% higher when compared with the data obtained from the room-temperature tests. The properties of ARALL 4 laminates have not been presented due to the unavailability of materials at this time.

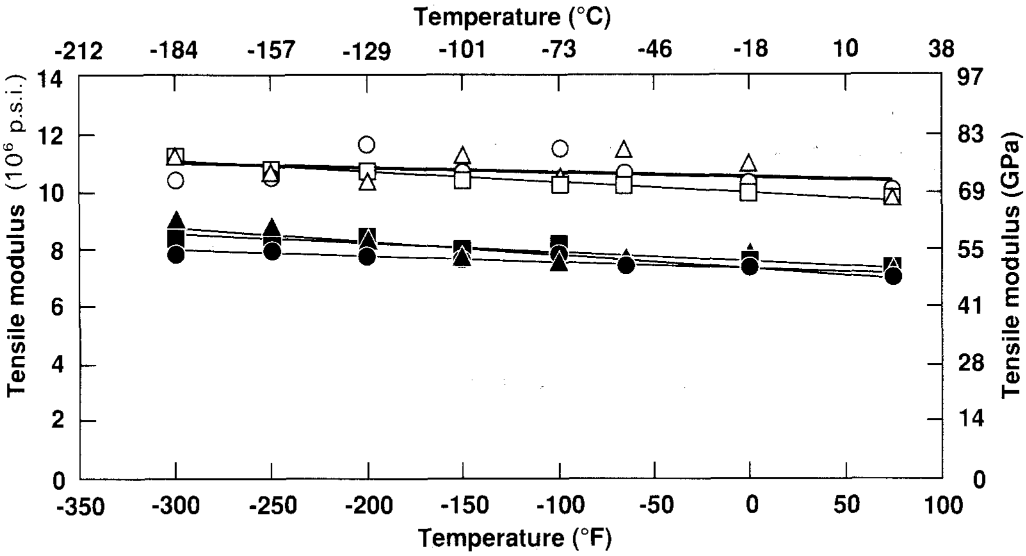


Figure 4 Tensile modulus versus cryogenic temperature for various ARALL laminates. For key, see Fig. 2.

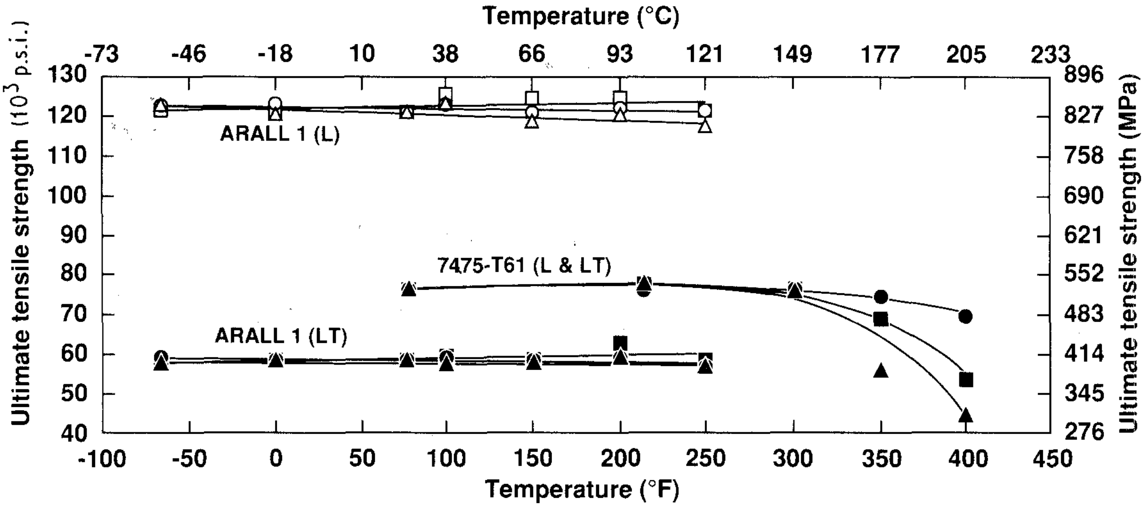


Figure 5 Comparison of ultimate tensile strength data of 3/2 ARALL 1 laminates with typical 7475-T61 sheet at room temperature after exposure. (○, ●) 1 h, (□, ■) 10 h, (△, ▲) 100 h. (○, □, △) L, (●, ■, ▲) LT.

3.1.1. Comparison with 7475-T61, 2024-T3, 7475-T761, and 2024-T81 monolithic aluminium alloy sheet

The L and LT ultimate tensile strength, tensile yield strength, and modulus of ARALL 1–4 laminates at cryogenic temperatures were also compared with typical strengths of monolithic aluminium alloy 7475-T61, 2024-T3, 7475-T761, and 2024-T81 sheet [11]. The ultimate tensile strength and tensile yield strength of ARALL laminates are significantly superior to those of aluminium alloy sheets in the L direction. However, the strengths of ARALL laminates in the LT direction are inferior to those for monolithic aluminium alloy sheets.

3.2. Long-term exposure to elevated and cryogenic temperatures

The results of tensile tests of ARALL 1–4 laminates in both the L and LT directions obtained at room temperature after exposure (– 65–400 °F or – 54–204 °C) for periods of 1, 10 and 100 h are plotted in Figs 5–16. Results of tensile tests of these laminates conducted at various temperatures (– 65–400 °F or – 54–204 °C for periods of 1, 10 and 100 h) are plotted in Figs 17–28. Results of the tensile tests conducted at room temperature without prior temperature exposure are also included. The ultimate tensile strengths and tensile yield strengths of the laminates in the L direction are considerably higher than the corresponding strengths in the LT direction. This same relationship exists between the L and LT directions for the tensile moduli.

3.2.1. Room-temperature properties after exposure

The ultimate tensile strengths, tensile yield strength, and moduli in both the L and LT directions for ARALL 1–4 laminates are plotted in Figs 5–16. The results of L and LT direction tests show that the ultimate tensile strengths, tensile yield strengths, and moduli remain nearly constant up to 250 °F (121 °C) for ARALL 1–3 laminates (see Figs 5–13).

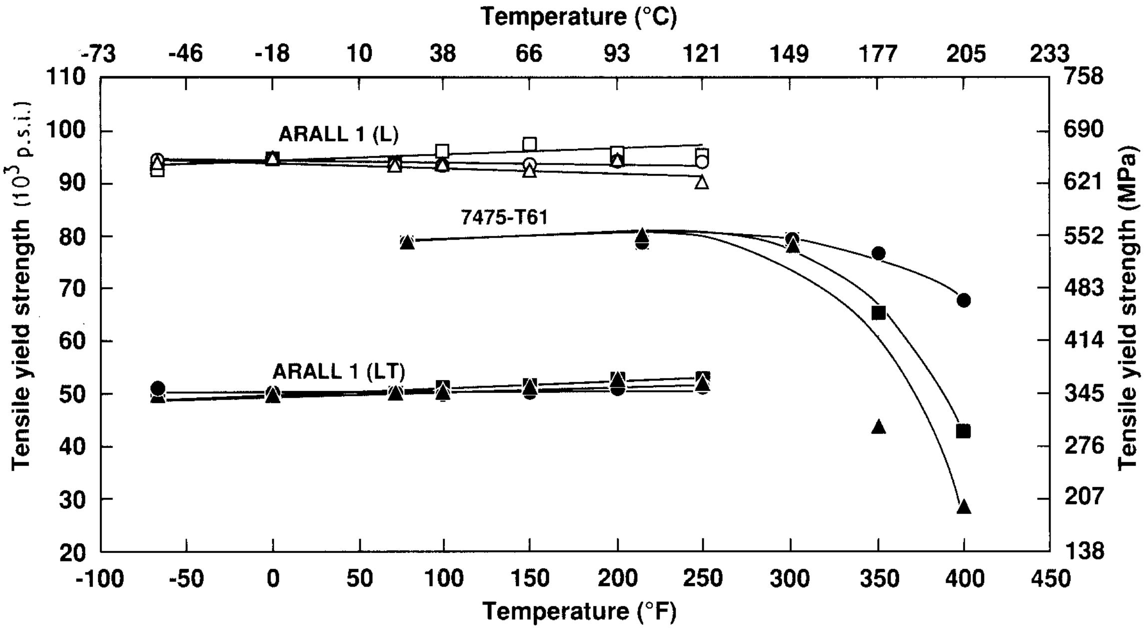


Figure 6 Comparison of tensile yield strength data of 3/2 ARALL 1 laminates with typical 7475-T61 sheet at room temperature after exposure. For key, see Fig. 5.

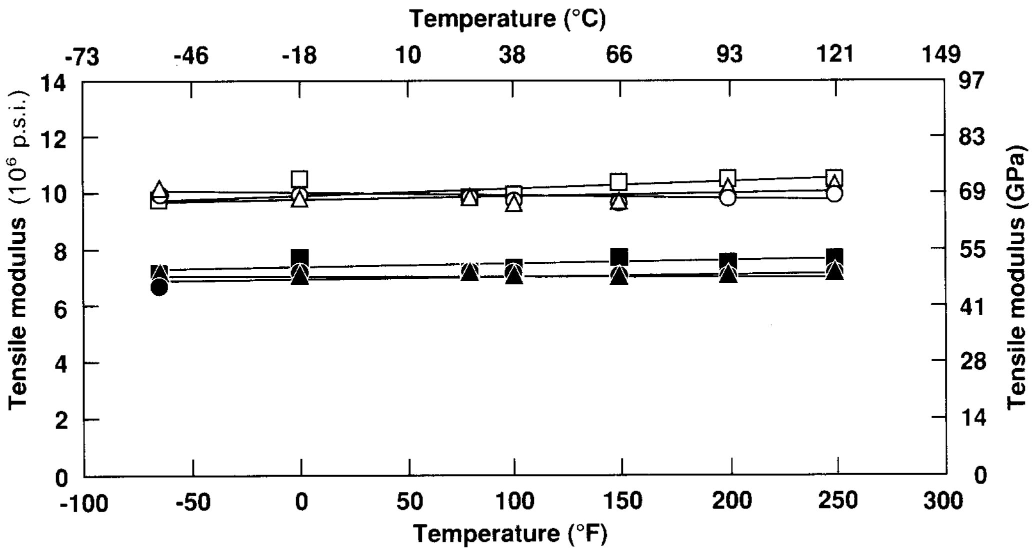


Figure 7 Effect of time and temperature on tensile modulus of ARALL 1 laminates at room temperature after exposure. For key, see Fig. 5.

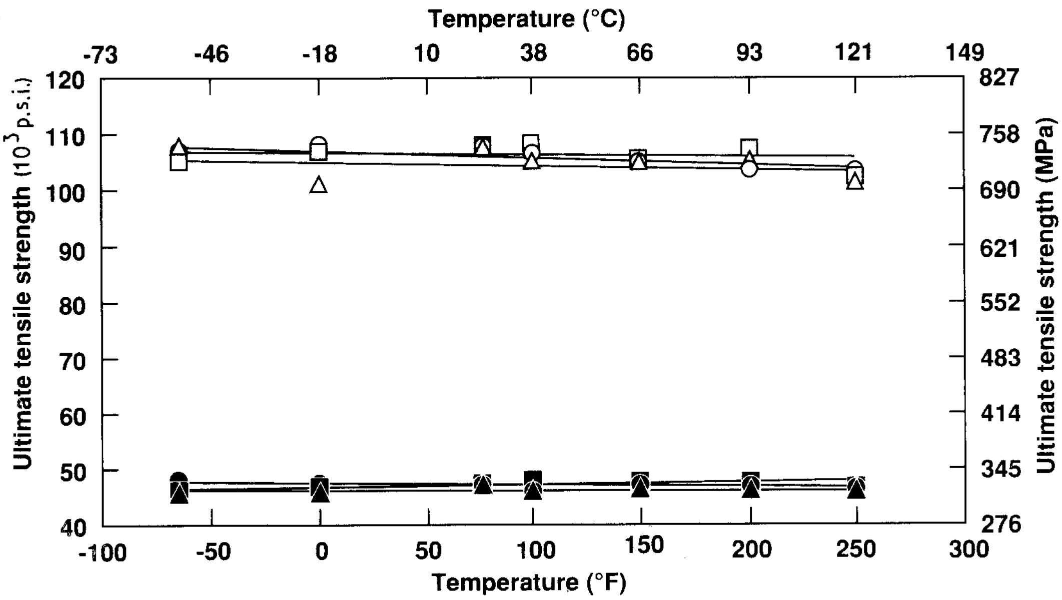


Figure 8 Effect of time and temperature on ultimate tensile strength of ARALL 2 laminates at room temperature after exposure. For key, see Fig. 5.

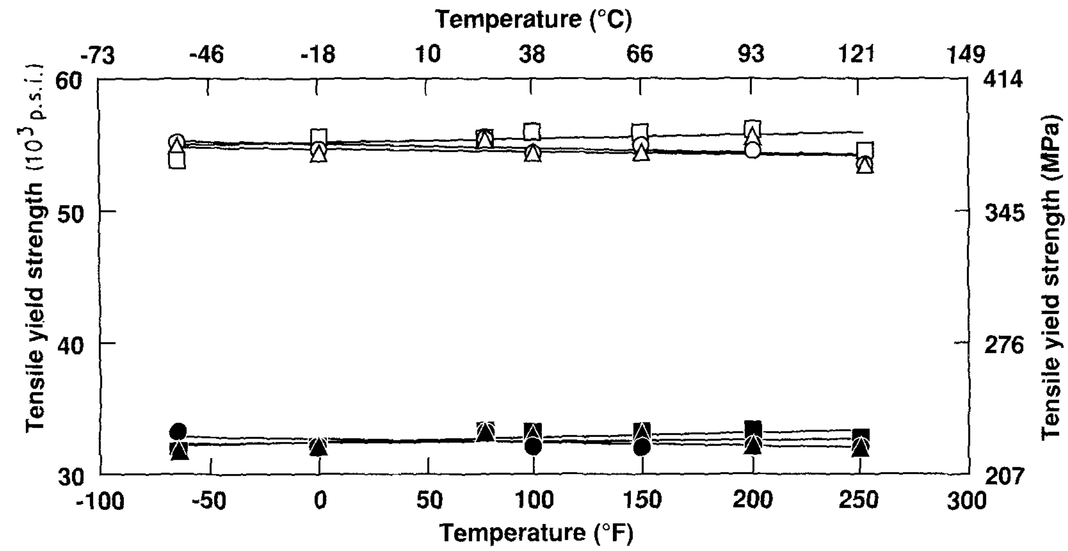


Figure 9 Effect of time and temperature on tensile yield strength of ARALL 2 laminates at room temperature after exposure. For key, see Fig. 5.

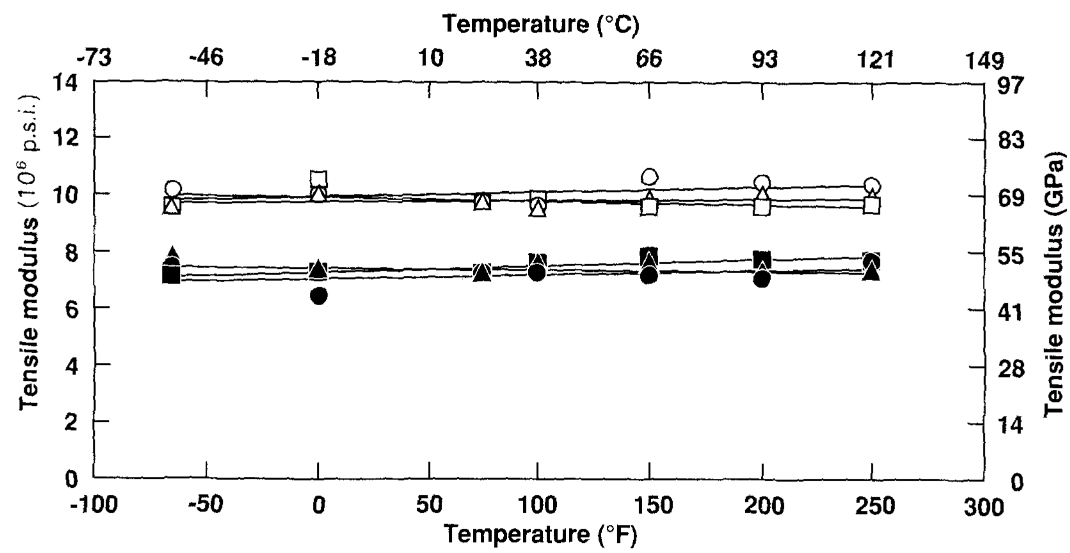


Figure 10 Effect of time and temperature on tensile modulus of ARALL 2 laminates at room temperature after exposure. For key, see Fig. 5.

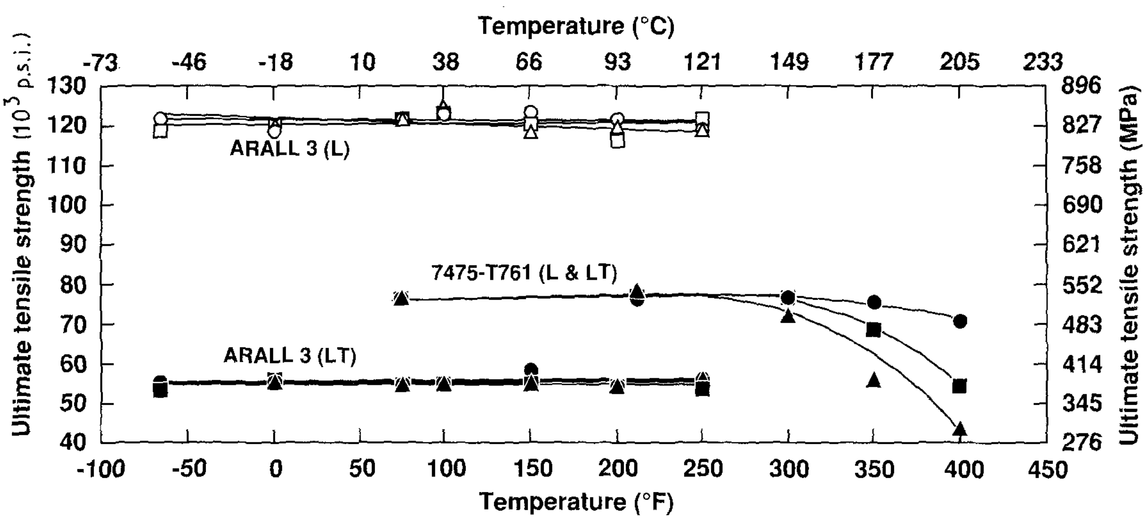


Figure 11 Comparison of ultimate tensile strength data of 3/2 ARALL 3 laminates with typical 7475-T761 sheet at room temperature after exposure. For key, see Fig. 5.

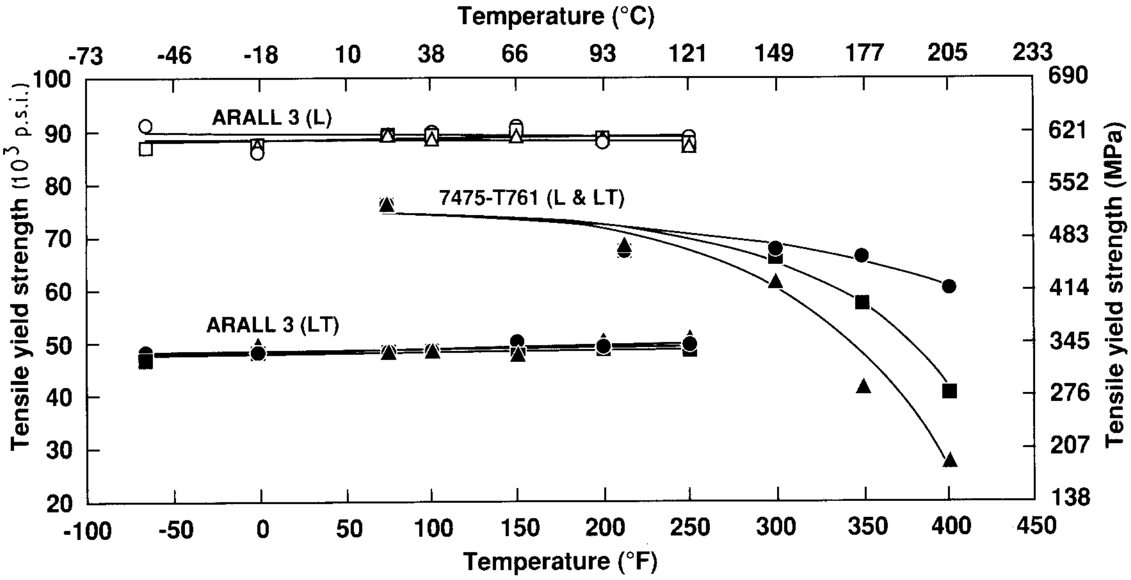


Figure 12 Comparison of tensile yield strength data of 3/2 ARALL 1 laminates with typical 7475-T761 sheet at room temperature after exposure. For key, see Fig. 5.

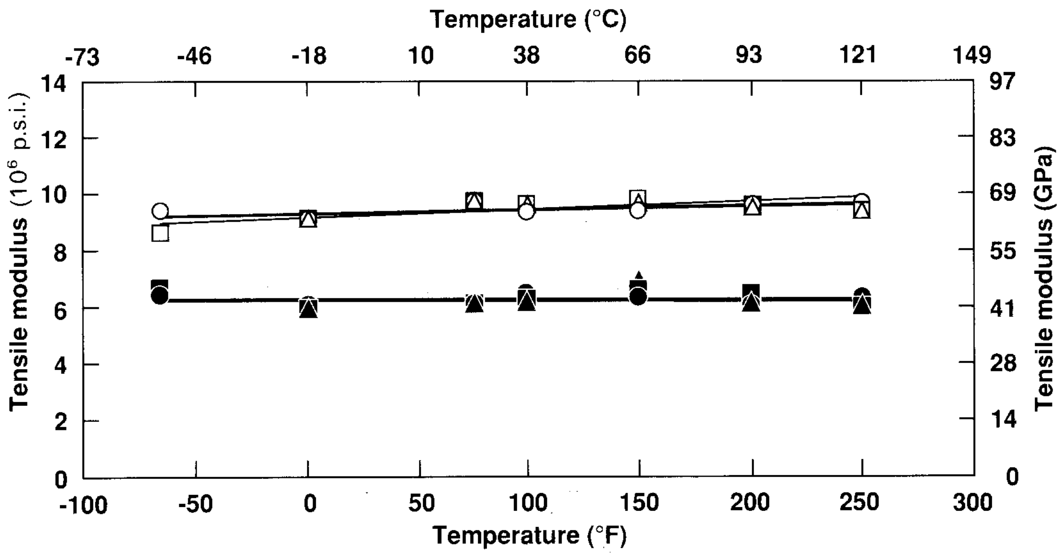


Figure 13 Effect of time and temperature on tensile modulus of ARALL 3 laminates at room temperature after exposure. For key, see Fig. 5.

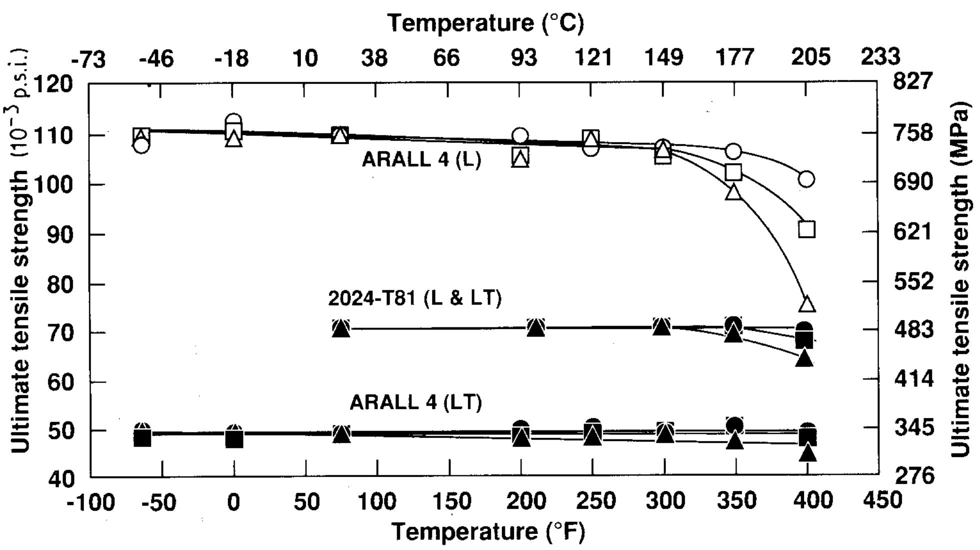


Figure 14 Comparison of ultimate tensile strength data of 3/2 ARALL 4 laminates with typical 2024-T81 sheet at room temperature after exposure. For key, see Fig. 5.

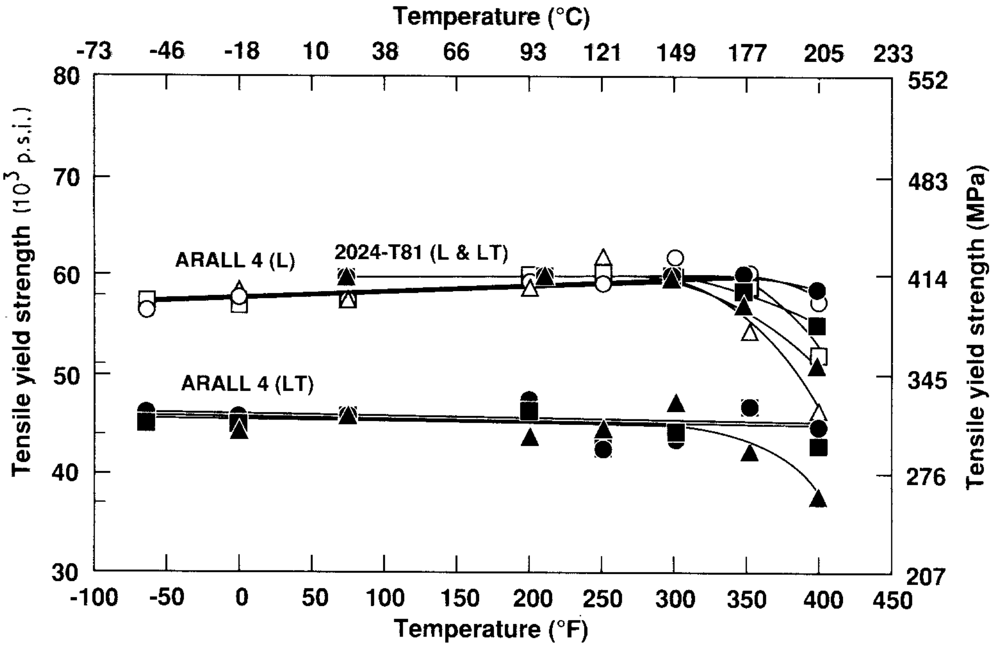


Figure 15 Comparison of tensile yield strength data of 3/2 ARALL 4 laminates with typical 2024-T81 sheet at room temperature after exposure. For key, see Fig. 5.

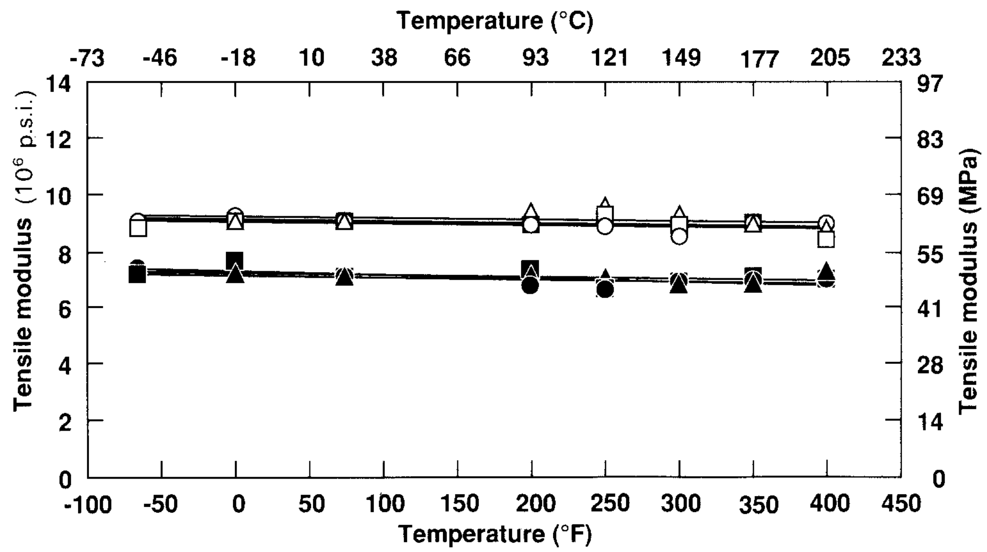


Figure 16 Effect of time and temperature on tensile modulus of ARALL 4 laminates at room temperature after exposure. For key, see Fig. 5.

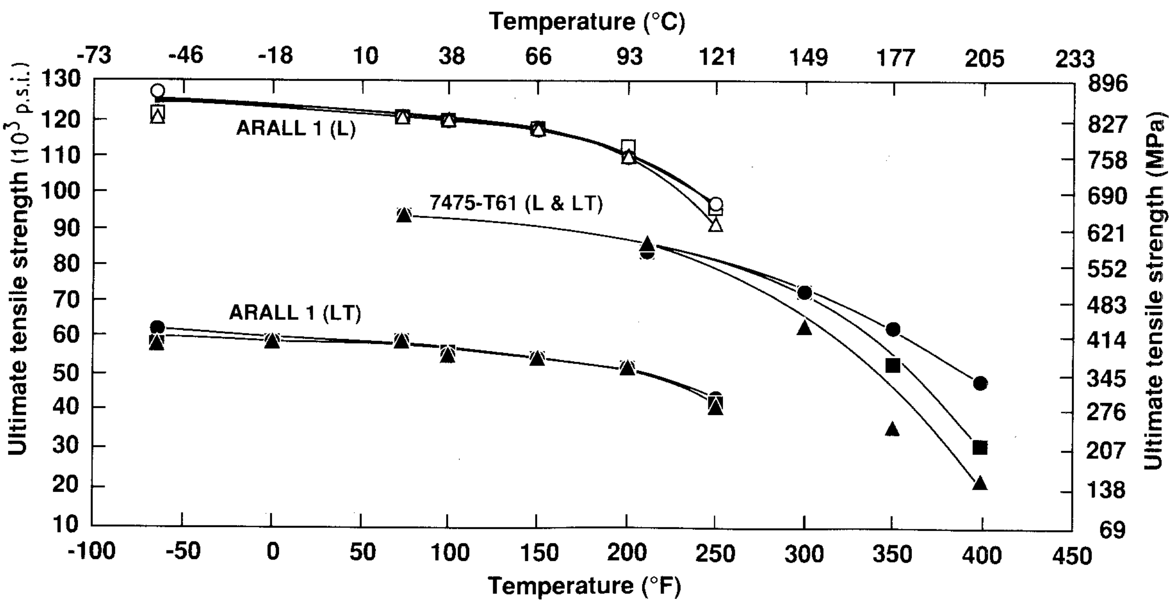


Figure 17 Comparison of ultimate tensile strength data of 3/2 ARALL 1 laminates with typical 7475-T61 sheet at cryogenic and elevated temperatures after exposure. For key, see Fig. 5.

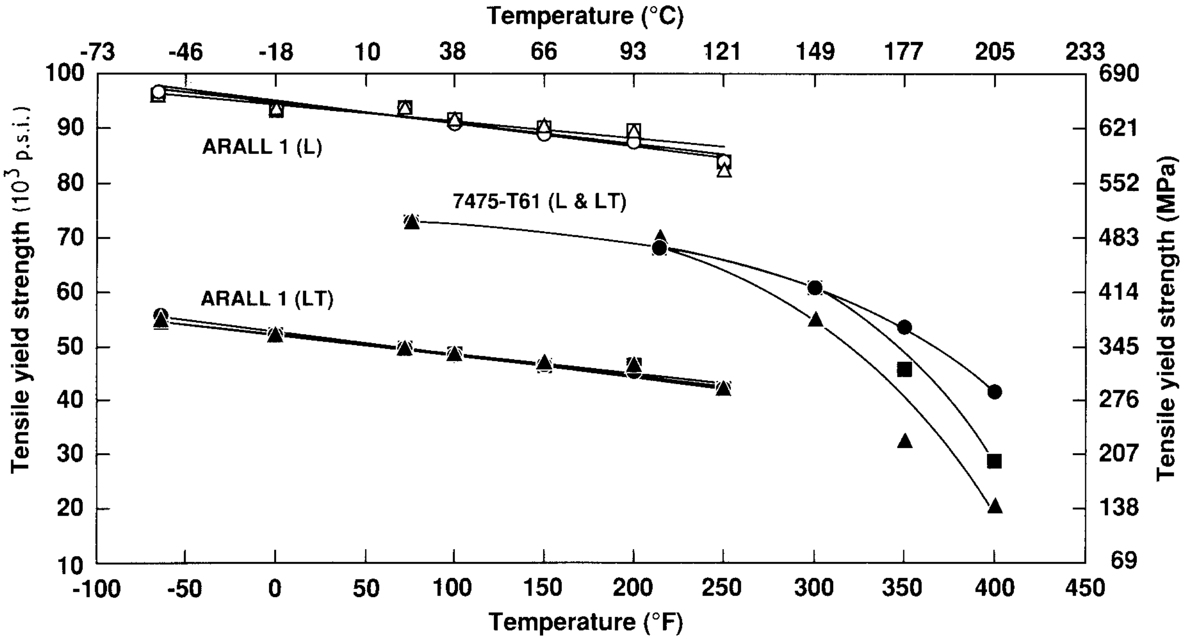


Figure 18 Comparison of tensile yield strength data of 3/2 ARALL 1 laminates with typical 7475-T61 sheet at cryogenic and elevated temperatures after exposure. For key, see Fig. 5.

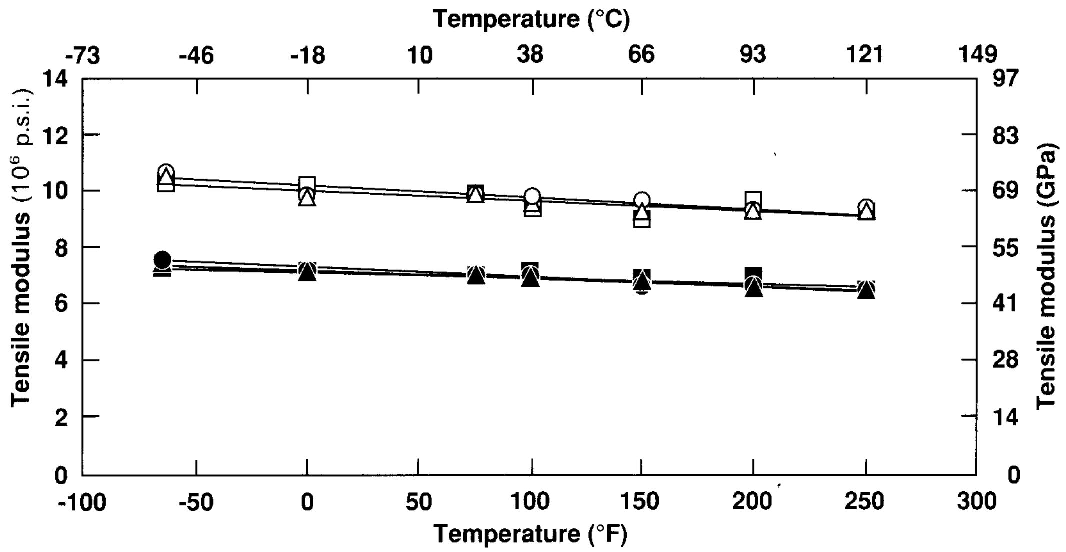


Figure 19 Effect of time and temperature on tensile modulus of ARALL 1 laminates at cryogenic and elevated temperatures after exposure. For key, see Fig. 5.

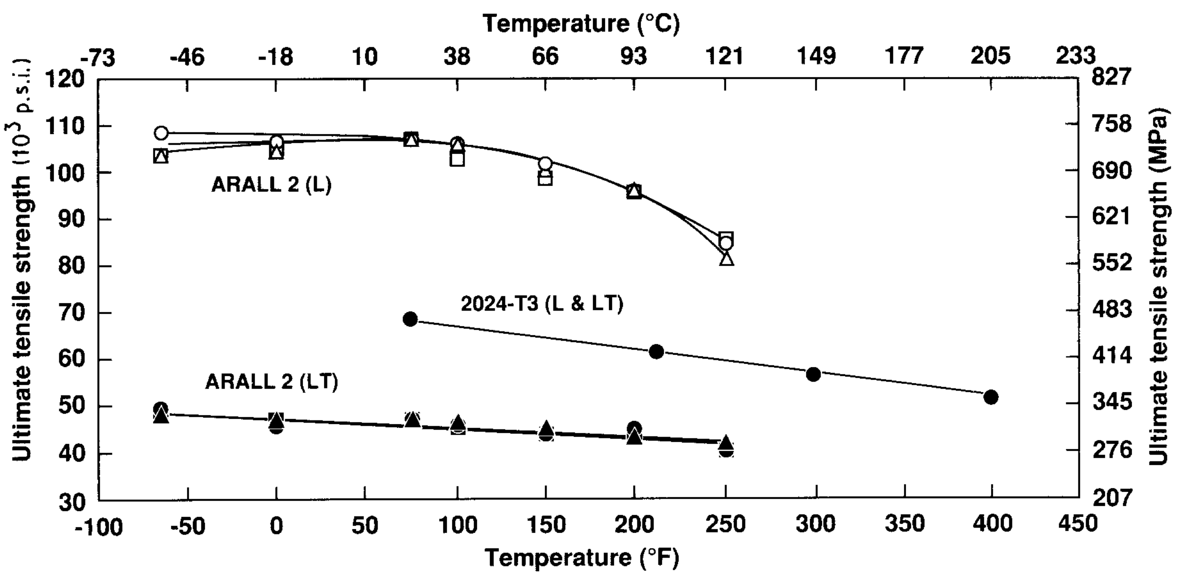


Figure 20 Comparison of ultimate tensile strength data of 3/2 ARALL 2 laminates with typical 2024-T3 sheet at cryogenic and elevated temperatures after exposure. For key, see Fig. 5.

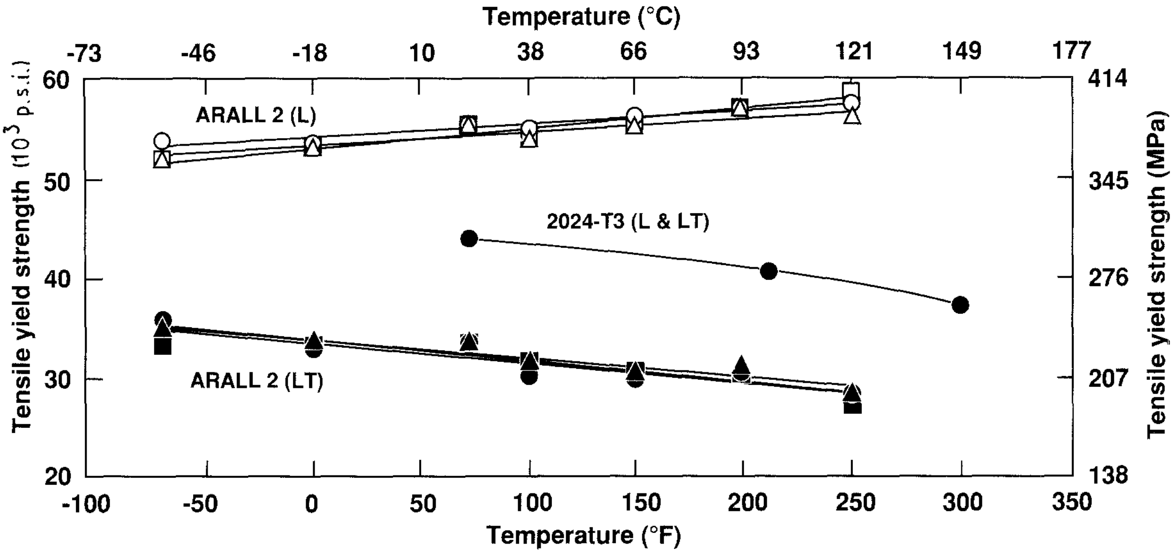


Figure 21 Comparison of tensile yield strength data of 3/2 ARALL 2 laminates with typical 2024-T3 sheet at cryogenic and temperatures after exposure. For key, see Fig. 5.

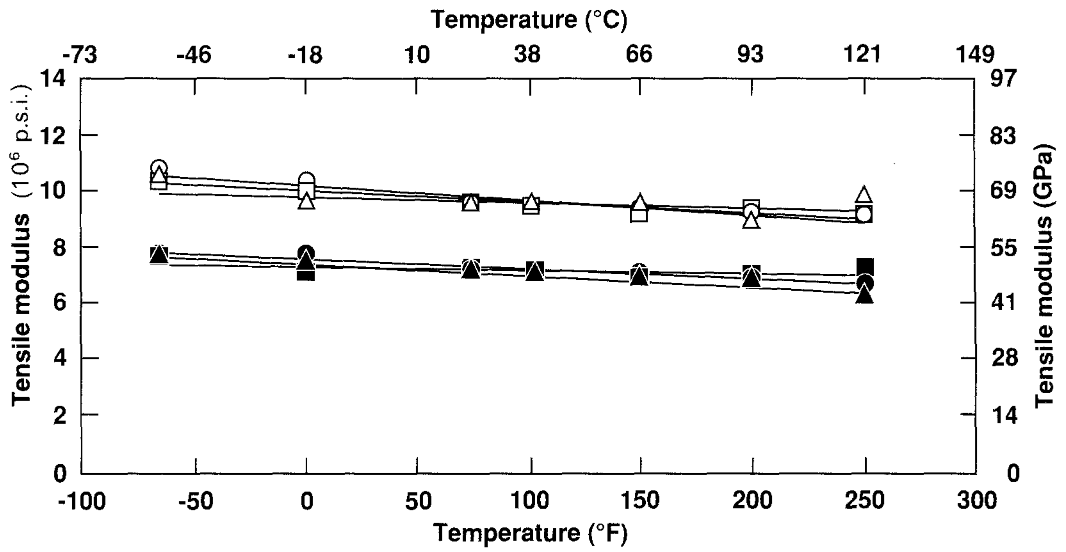


Figure 22 Effect of time and temperature on tensile modulus of ARALL 2 laminates at cryogenic and elevated temperatures after exposure. For key, see Fig. 5.

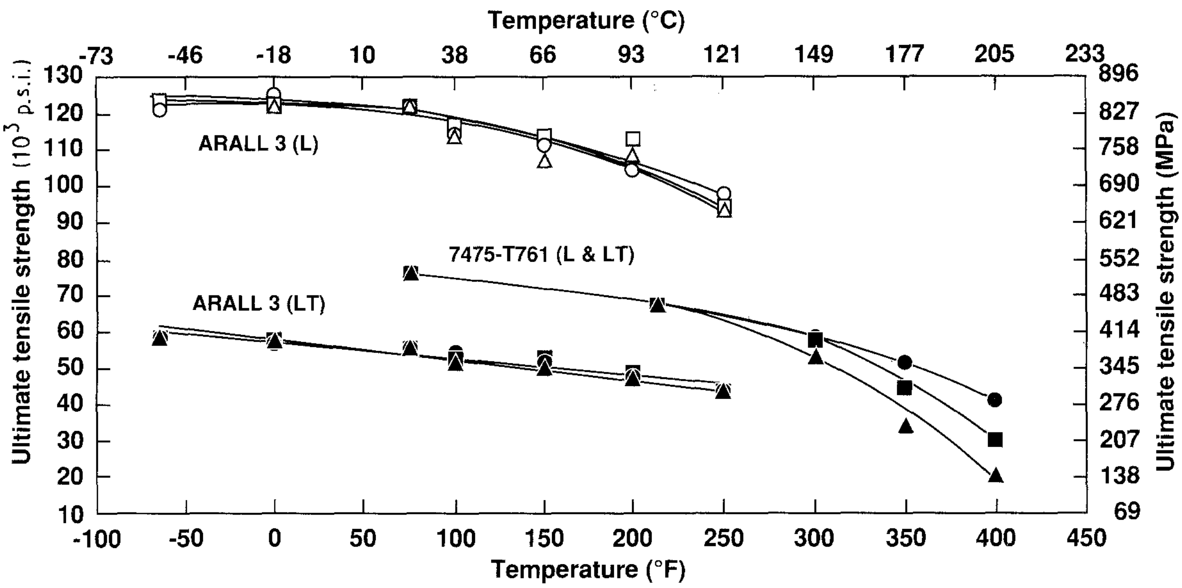


Figure 23 Comparison of ultimate tensile strength data of 3/2 ARALL 3 laminates with typical 7475-T761 sheet at cryogenic and elevated temperatures after exposure. For key, see Fig. 5.

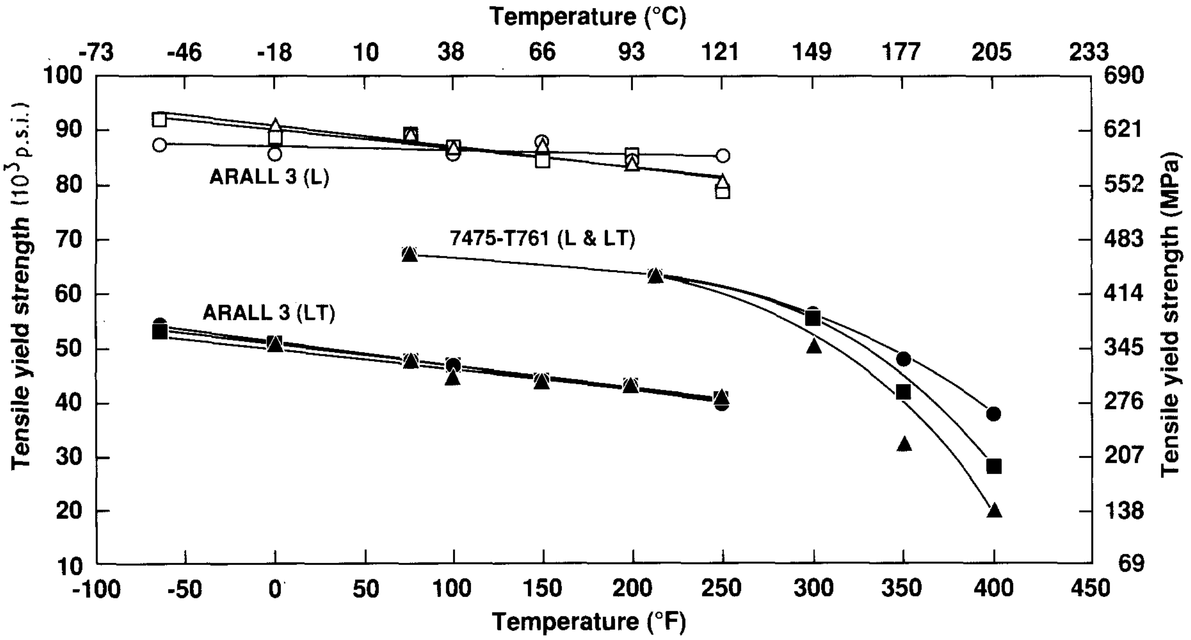


Figure 24 Comparison of tensile yield strength data of 3/2 ARALL 3 laminates with typical 7475-T761 sheet at cryogenic and elevated temperatures after exposure. For key, see Fig. 5.

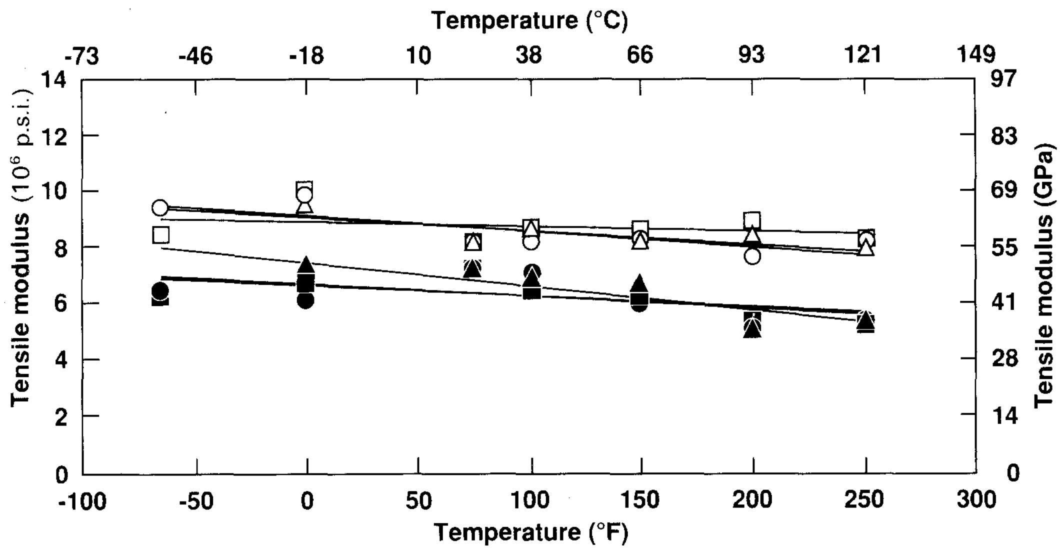


Figure 25 Effect of time and temperature on tensile modulus of ARALL 3 laminates at cryogenic and elevated temperatures after exposure. For key, see Fig. 5.

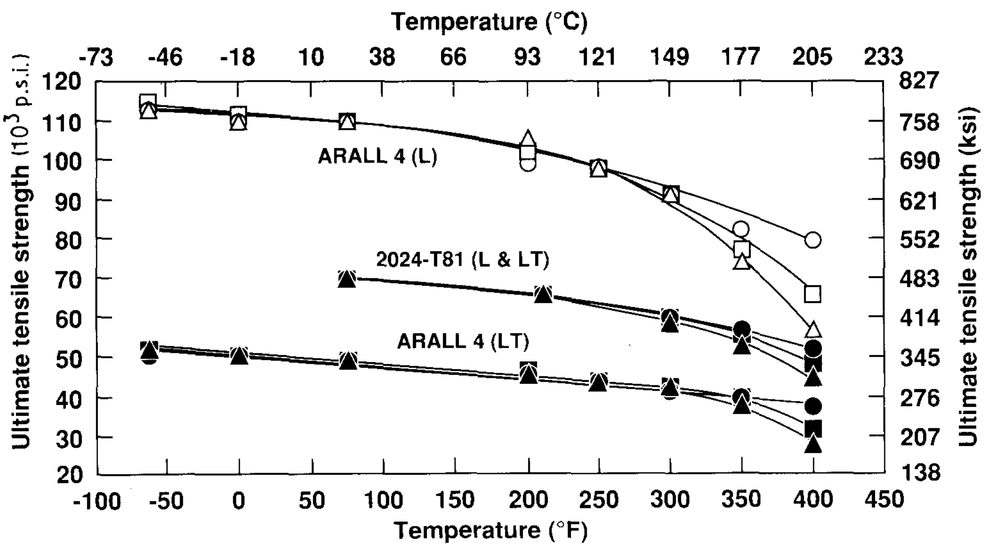


Figure 26 Comparison of ultimate tensile strength data of 3/2 ARALL 4 laminates with typical 2024-T81 sheet at cryogenic and elevated temperatures after exposure. For key, see Fig. 5.

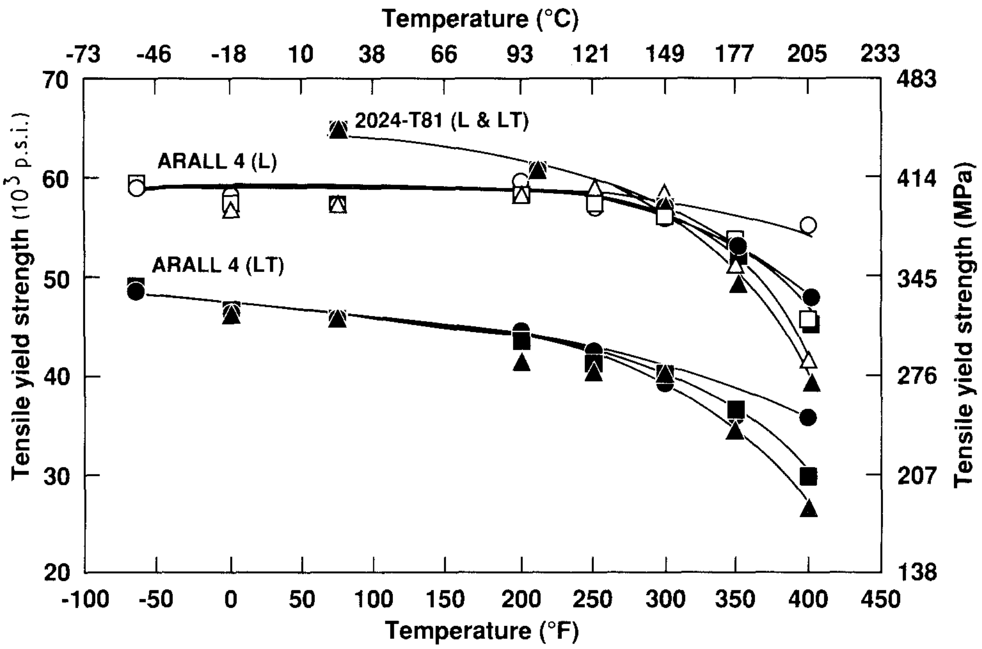


Figure 27 Comparison of tensile yield strength data of 3/2 ARALL 4 laminates with typical 2024-T81 sheet at cryogenic and elevated temperatures after exposure. For key, see Fig. 5.

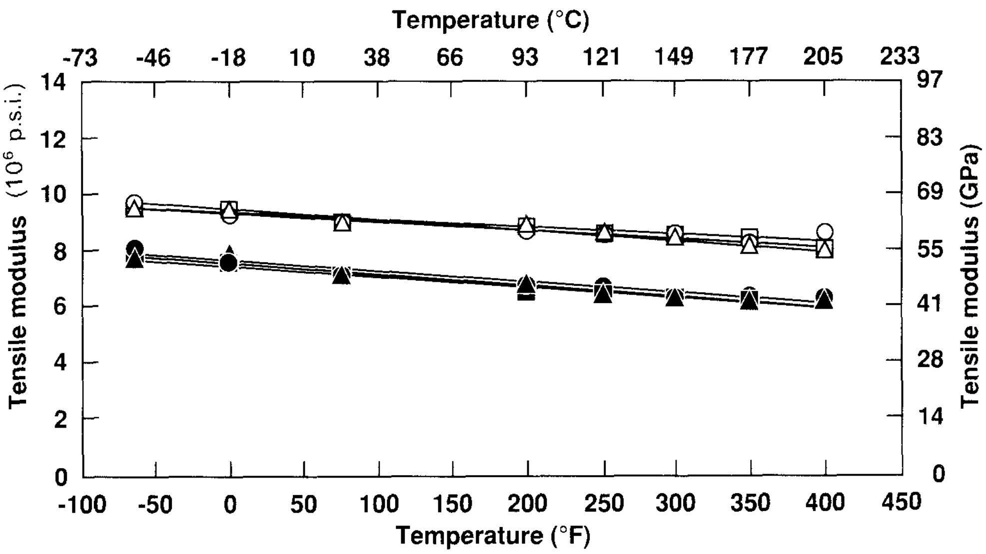


Figure 28 Effect of time and temperature on tensile modulus of ARALL 4 laminates at cryogenic and elevated temperatures after exposure. For key, see Fig. 5.

For ARALL 4 laminates, the properties remain unchanged up to 350 °F (177 °C), except for the strengths of the 100 h exposure at 350 °F (177 °C) which decreased by about 10%. The strengths at 400 °F (204 °C) are more variable and lower than those at lower temperatures. The longitudinal ultimate tensile strengths at 10 and 100 h at 400 °F (204 °C) decreased about 9% and 25%, respectively. However, exposure temperature had a small effect on the transverse tensile strengths. The data are plotted in Figs 14–16. The tensile moduli in both the L and LT directions remain fairly constant up to 400 °F (204 °C). This demonstrates that ARALL 4 laminates remain stable at temperatures up to 350 °F (177 °C).

3.2.2. Elevated and cryogenic temperature properties after exposure

Figs 17–28 show that the results of tensile properties at elevated and cryogenic temperature tests in both the L and LT directions for ARALL 1–4 laminates For ARALL 1–3 laminates, the mechanical properties decrease as the temperatures increase. Contrarily, the tensile yield strength of ARALL 2 laminates in the L direction has the opposite trend. The explanation remains unknown. At 250 °F (121 °C) the ultimate tensile strengths decrease about 20%–25%, the tensile yield strengths decrease about 5%–10%, and the moduli decrease roughly 5%–10% in both the L and LT directions. These changes can be easily seen in Figs 17–25.

In the lower temperature range (– 65 °F or – 54 °C) of ARALL 4 laminates, the strengths show a small increase over the room-temperature strengths; however, at elevated temperatures the strengths decrease as the temperature increases. For the longitudinal ultimate tensile strength using the result of room temperature as a baseline, the strength reduction at 400 °F (204 °C) is shown to be 25%, 38%, and 47% for 1, 10 and 100 h exposure, respectively. The tensile yield strength decreases as the temperature increases in the range 300 °F (149 °C) and 400 °F (204 °C). The tensile modulus increases at the lower temperature, but shows a tendency to decrease at high temperatures. The results are plotted in Figs 26–28.

3.2.3. Comparison with 7475-T61, 2024-T3, 7475-T761, and 2024-T81 monolithic aluminium alloy sheet

The L and T ultimate tensile strength, tensile yield strength, and modulus of ARALL 1–4 laminates at room temperature (no prior temperature exposure), and at the other exposure conditions are also compared with typical strengths of monolithic aluminium alloy 7475-T61, 2024-T3, 7475-T761, and 2024-T81 sheet [11]. Comparisons between ARALL laminates properties and aluminium alloys sheet properties are shown in Figs 5–28. In the L direction, the ultimate tensile strength and tensile yield strength of ARALL laminates are significantly superior to those of aluminium alloy sheets. Contrarily, the strengths of ARALL laminates in the LT direction are inferior to those for monolithic aluminium alloy sheets. However, the mechanical properties of ARALL 1–3 laminates are superior to those of 7475-T61, 2024-T3, and 7475-T761 sheets at 250 °F (~ 121 °C) and mechanical properties of ARALL 4 laminates are superior to those of 2024-T81 sheet at 400 °F (204 °C).

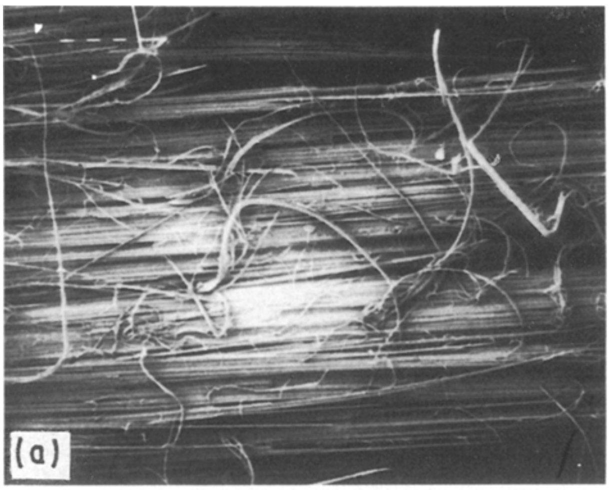
3.2.4. Fracture topography

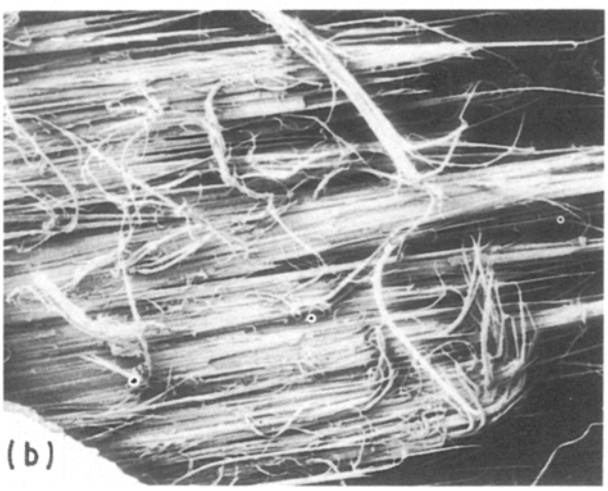
In this study, fractured ARALL 4 laminates specimens were chosen for investigation of the failure modes using a scanning electron microscope. For longitudinal specimens, fibre pull-out and fibrillation and interface–matrix shear failure mode were commonly observed in aramid/epoxy layer of ARALL laminates. The fracture characteristics changed greatly at 400 °F (204 °C) as can be seen in Figs 29 and 30. At the lower temperatures, the fracture surfaces were relatively featureless. The longitudinal specimens also showed a local failure without global longitudinal splitting; this was the broom straw effect described by Wardle and Steenkamer [12]. This shows that the aluminium alloy helps prevent broom straw effect. For the transverse specimens, matrix tensile failure and constituent debonding/fibre splitting were ordinarily observed in the aramid/epoxy layer (see Figs 31 and 32). In the high-temperature range of 400 °F (204 °C), the fibre–matrix interface debonding was remarkably dominant. This will cause the laminate strength reduction.

4. Conclusions

1. In short-term exposure to cryogenic temperatures the tensile properties of ARALL 1–3 laminates either remain the same or tend to increase slightly as the temperature decreases. The tensile strengths have about a 3–8% increase in the longitudinal direction and have a 15–30% increase in the transverse direction.

2. Ultimate tensile strength, tensile yield strength, and moduli remain nearly constant for temperatures up to 250 °F (121 °C) for ARALL 1–3 laminates, and up to 350 °F (177 °C) for ARALL 4 laminates when tested at room temperature after exposure. At 400 °F (204 °C), a significant decrease in strength appeared





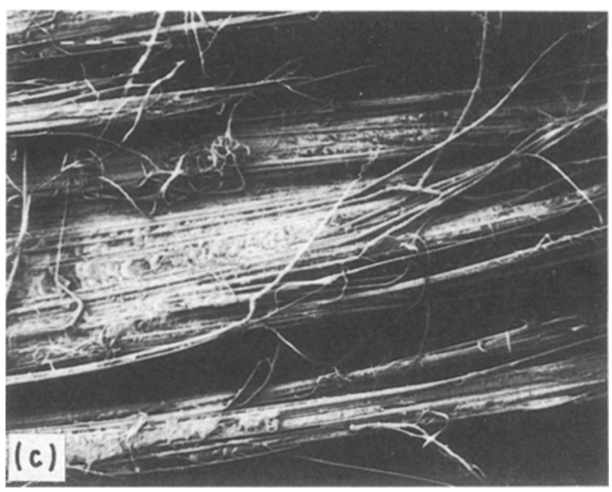


Figure 29 Temperature dependence of tensile fracture surface (L), of ARALL 4 laminates: (a) − 65 °F (− 54 C), (b) 75 °F (24 °C), (c) 400 °F (204 °C). × 70

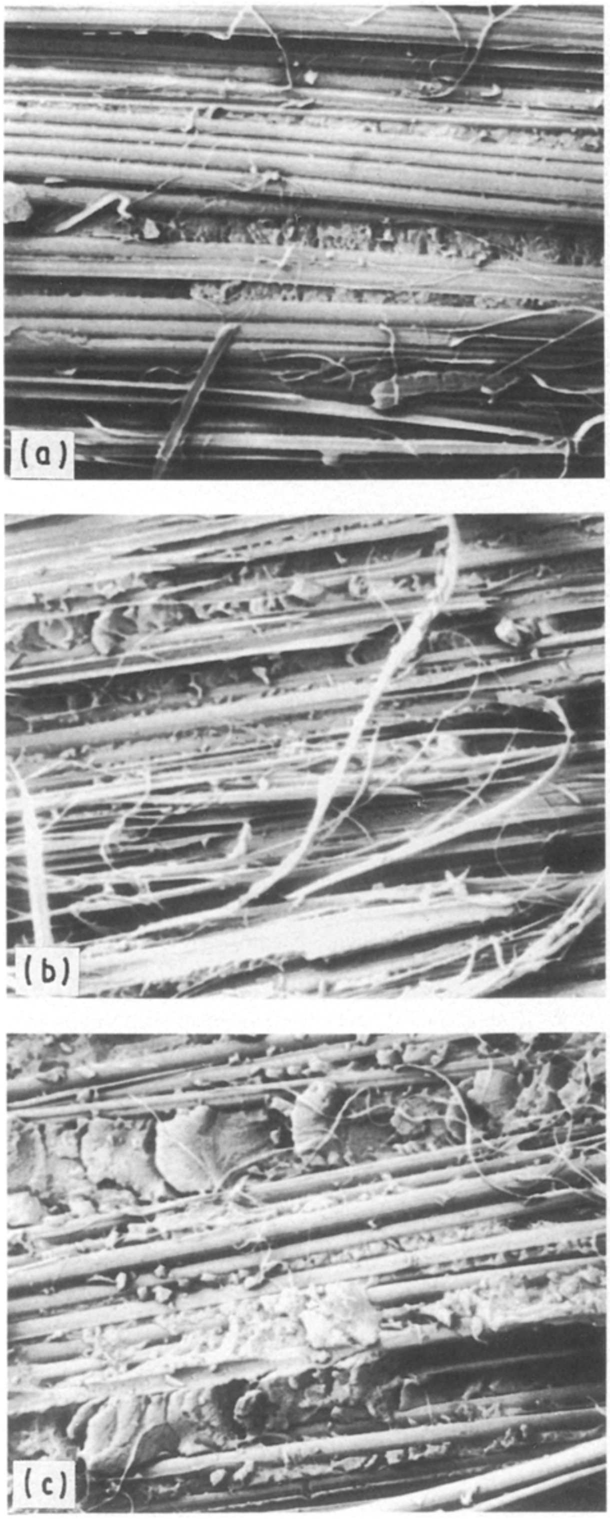


Figure 30 Temperature dependence of tensile fracture surface (L), of ARALL 4 laminates showing interface–matrix shear failure and fibre pull-out/fibrillation: (a) – 65 °F (– 54 °C), (b) 75 °F (24 °C), (c) 400 °F (204 °C). × 350

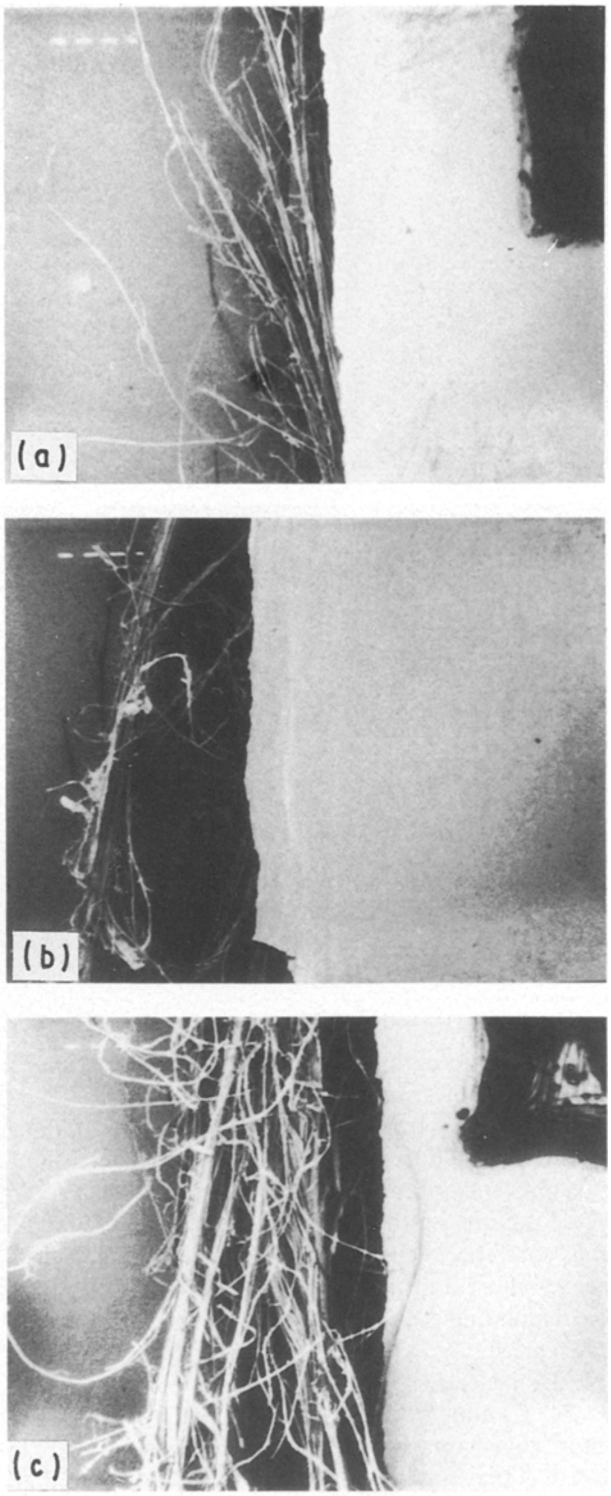
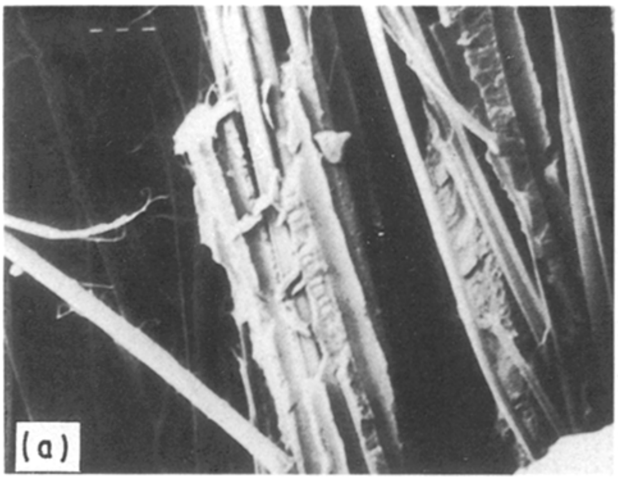


Figure 31 Temperature dependence of tensile fracture surface (T), of ARALL 4 laminates: (a) – 65 °F (– 54 °C), (b) 75 °F (24 °C), (c) 400 °F (204 °C). × 20

for ARALL 4 laminates. However, the tensile moduli of ARALL 4 laminates show no change up to 400 °F (204 °C).

3. The ultimate tensile strength, tensile yield strength, and moduli determined after exposure to a cryogenic or elevated temperature decrease as the temperature increases. The decrease in strengths at the desired temperatures were found to be insignificant at 250 °F (121 °C) for ARALL 1–3 laminates and at 400 °F (204 °C) for ARALL 4 laminates for 1, 10 and 100 h exposure times.

4. In the longitudinal direction, the ultimate tensile strength and tensile yield strength of ARALL laminates are shown to be superior to those of 7475-T61, 2024-T3, 7475-T761 and 2024-T81 monolithic aluminium alloys. The properties of ARALL 4 laminates are much better than those of 2024-T81 sheet at 400 °F (204 °C).



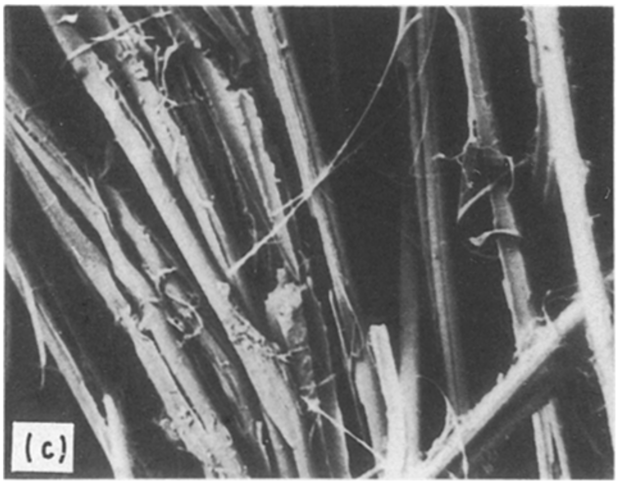


Figure 32 Temperature dependence of tensile fracture surface (T) of ARALL 4 laminates showing fibre and matrix separation at the interface and fibre splitting: (a) $-65\,^{\circ}$F ($-54\,^{\circ}$C), (b) 75 °F (24 °C), (c) 400 °F (204 °C). ×350

5. SEM fractography of the longitudinal specimens in the layer of aramid/epoxy shows that fibre pull-out/fibrillation and interface–matrix shear failure dominate the failure mode. In addition, the aluminium layer prevents multiple global longitudinal splits.

6. Fracture in the layer of aramid/epoxy of the transverse specimens in mainly caused by the matrix tensile failure and fibre splitting. Fibre–matrix interface debonding is dominant when the test temperature is increased.

7. In general, the fracture surfaces at $-65\,^{\circ}$F ($-54\,^{\circ}$C) and 75 °F (24 °C) were similar in that the fibres stayed intact with epoxy. However, at 400 °F (204 °C), the fracture surfaces were different in that the fibres separated to cause the laminate strength reduction.

Acknowledgements
The author thanks J. F. Dalton and Ms Ling L. Wu who contributed to the research described in this paper.

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Received 2 July 1991
and accepted 1 May 1992