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Effect of temperature and strain rate on tensile mechanical properties of ARALL-1 laminates

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The combined effect of temperature and strain rate of the mechanical properties for unidirectional 3/2 ARALL®-1 laminates was studied. In this paper, the effect of strain rates from 0.000 83–0.833 min^{-1} on tensile behaviour at temperatures up to 250 °F (~121 °C) has been conducted. It is demonstrated that tensile strength, tensile modulus, and fracture strain are found to depend on temperature and strain rate. However, the effect of strain rates at 75 °F (~24 °C) and 180 °F (~82 °C) was found to be insignificant except the lowest strain rate at 180 °F. It was also observed that the tensile yield strength decreased as the strain rate decreased. The tensile properties were moderately reduced at high temperatures and were higher at high strain rates than at low strain rates. The temperature effect is more significant than that due to the strain rate. Scanning electron photomicrographs of the fracture surfaces observed in the aramid/epoxy layer of ARALL-1 laminates at the lowest strain rate are shown to be significantly different only at 250 °F (~121 °C). But this phenomenon is not obvious when the highest strain rate is employed.

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 alternative 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 [1–8] show ARALL laminates have outstanding fatigue properties in comparison to 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 static properties significantly higher than conventional high-strength aluminium alloys, 7475-T61 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, lower wings and tail skins. Attendant design/trade studies on these components have identified the potential for significant weight savings of more than 30% over standard aerospace metals (see [7]).

The stability of mechanical properties over the potential operating temperatures and strain rates is very important for structural applications of composite materials. ARALL laminates are composed of a prepregnated material which is viscoelastic in nature, therefore it is worthwhile addressing whether properties are affected. More recently, other researchers conducted independent experimental investigations to determine the temperature/strain rate effects in aluminium alloys [11] and aramid/epoxy composites [12]. It was reported that no significant strain rate was found in aluminium alloys [11]. However, the aramid/epoxy material showed a definite increase in both modulus and strength with strain rate [12] because the nature of viscoelasticity in this case has more rate-dependent properties. This report deals with a study of the combined effect of temperature and strain rate on the tensile properties of ARALL laminates.

2. Experimental procedure

2.1. Material

ARALL-1 laminates, in a 3/2 configuration, were selected for this study. They have 0.053 in. (~0.135 cm) nominal thickness and consist of three 0.012 in. (~0.030 cm) thick 7475-T61 aluminium sheet layers and two layers of DuPont unidirectional aramid fibres impregnated with 3M's AF-163-2U, 250 °F (~121 °C) cure adhesive. The prepreg layer

*ARALL was originally an acronym (ARamid ALuminium Laminates) derived by Delft University of Technology. ARALL laminates are now an Alcoa registered trademark.

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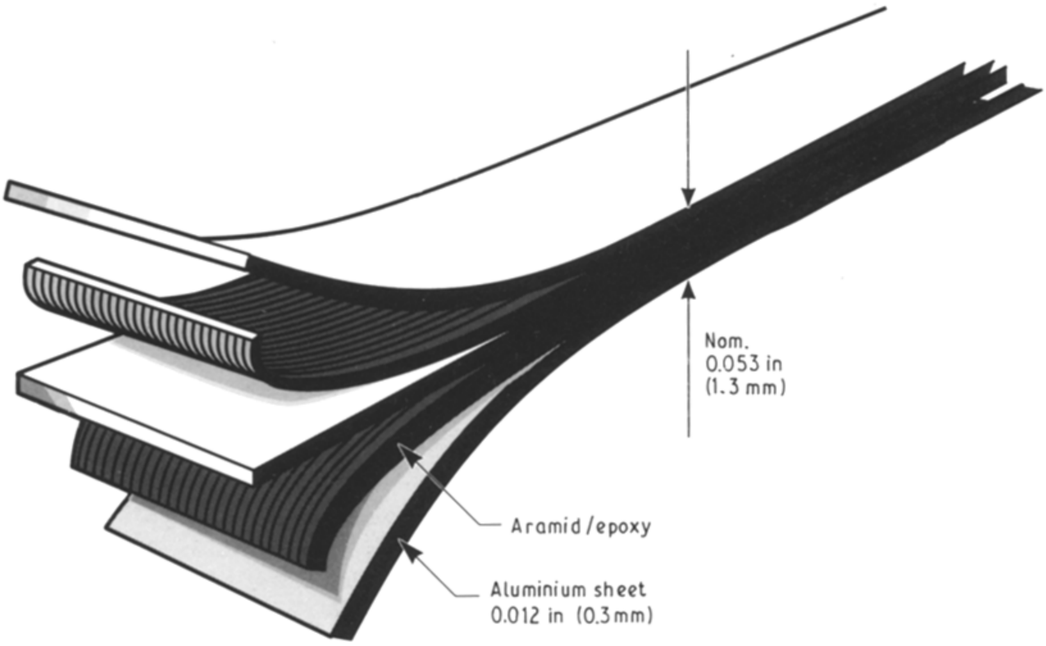


Figure 1 Alcoa ARALL® laminates schematic of standard 3/2 layup.

fibre-adhesive ratio is 50/50 by weight, and the fibre axis and aluminium sheet rolling directions coincide. Curing results in a residual stress state that places the metal layers in tension and fibres in compression. However, ARALL-1 laminates are given a nominal 0.4% permanent stretch to reverse the residual stress state to compression in the aluminium layers and tension in the higher strength aramid fibres. Not only do ARALL laminates, in the as-cured state, have excellent fatigue properties, but also the stretching operation makes ARALL laminates practically insensitive to fatigue crack growth [7]. The specimens were longitudinal, with loading direction parallel to the fibres. Specimens were tabless straight-sided [10] and fabricated in accordance with ASTM D-3039.

2.2. Test procedure

The tensile tests were performed on a 10^5 p.s.i. (10^3 p.s.i. = 6.89 N mm^{-2}) Instron Testing Machine with approximate strain rates from 0.000 83–0.833 min^{-1} and over a range of temperature from 75–250 °F (~ 24–121 °C). The strain was measured using an extensometer, and the strain rate was recorded as the crosshead speed of the tensile testing machine divided by the gauge length of the specimen. All specimens were heated to the desired temperature, held at temperature for 5 min, then pulled at the desired strain rate.

Parameters of ultimate tensile strength, tensile yield strength, approximate modulus, and the strain at failure were recorded.

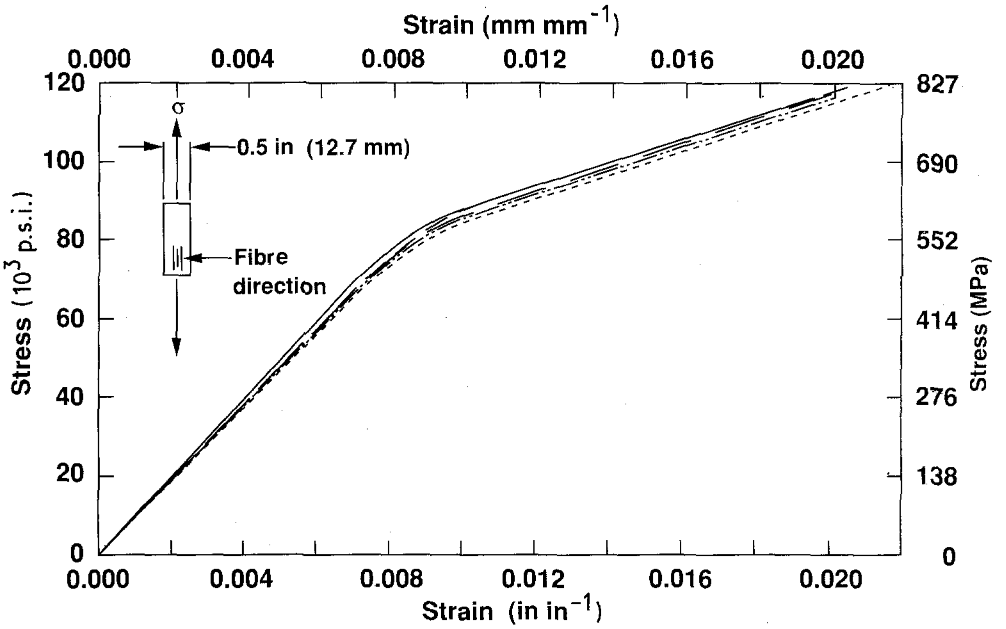


Figure 2 Stress–strain curves at various strain rates for 3/2 ARALL-1 laminates at 75 °F (24 °C). (——) 0.000 83 min^{-1}; (– – –) 0.0083; (— – - —) 0.017; (— —) 0.083; (— - —) 0.833.

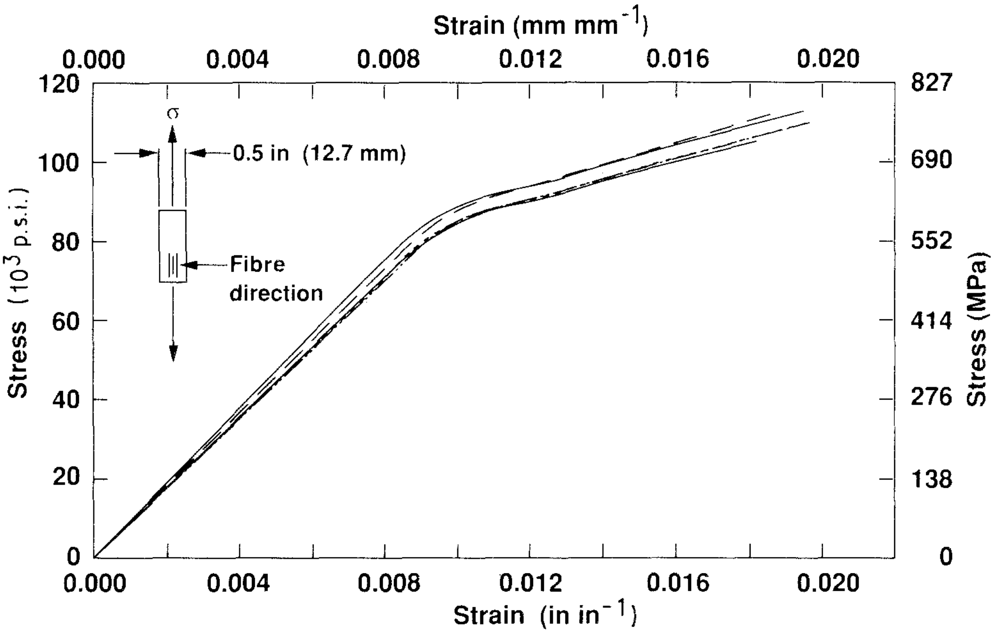


Figure 3 Stress–strain curves at various strain rates for 3/2 ARALL-1 laminates at 180 °F (82 °C). (——) 0.000 83 min^{-1}; (- - -) 0.0083; (— -- —) 0.017; (——) 0.083; (- — -) 0.833.

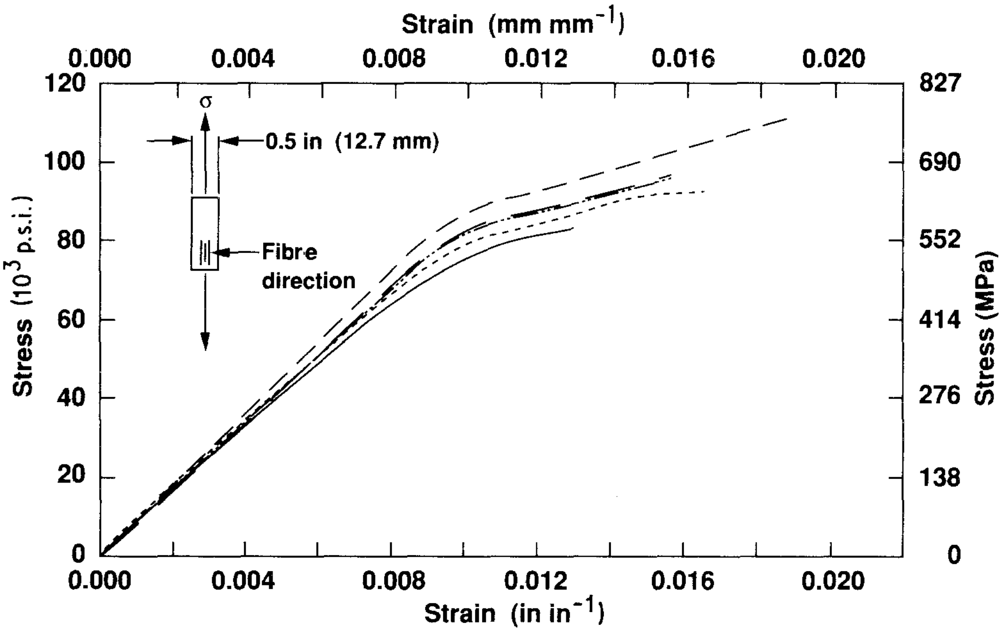


Figure 4 Stress–strain curves at various strain rates for 3/2 ARALL-1 laminates at 250 °F (121 °C). (——) 0.000 83 min^{-1}; (- - -) 0.0083; (— -- —) 0.017; (——) 0.083; (- — -) 0.833.

At least five specimens were tested at each condition. Data are the average of these five tests. Finally, the fracture surfaces were microscopically examined using a scanning electron microscope (SEM).

2.3. Data analysis

General linear models associated with least-squares means were performed in a statistical comparison of the average strengths, moduli, and strains at failure for each condition of strain rate and temperature.

3. Results and discussion

3.1. Stress–strain behaviour

Representative stress (σ)-strain (ε) curves for different strain rates obtained at 75, 180, and 250 °F (24, 82 and 121 °C) are shown in Figs 2–4. At 75 °F, it was found that the strain rate had little effect on σ–ε behaviour as shown in Fig. 2. However, the σ–ε curves open up as the strain rate increases at 180 and 250 °F. The apparent moduli at 75 and 180 °F remain roughly constant upon changing the strain rate from 0.000 83 min^{-1} to 0.833 min^{-1} (Figs 2 and 3), while at 250 °F some change is noted (Fig. 4).

3.2. Tensile mechanical properties

The average tensile mechanical properties of the combined effect between temperature and strain rate of ARALL-1 laminates are listed in Table I. The results of the statistical analysis on the ultimate tensile strength and tensile yield strength at room temperature, 75 °F, are shown in Figs 5 and 6. Figs 5a and 6a

TABLE I Tensile mechanical properties[a] of temperature and strain rate effects of 3/2 ARALL-1 laminates

Temperature °F (°C)	Strain rate (min^{-1})	UTS[b] (10^3 p.s.i.) (MPa)	TYS[c] (10^3 p.s.i.) (MPa)	Approximate (10^6 p.s.i.) modulus (GPa)	Strain at failure (%)
	0.000 83	116 (800)	90 (621)	9.8 (68)	2.00
	0.008 3	118 (814)	89 (614)	9.6 (66)	2.13
75 (24)	0.017	118 (814)	90 (621)	9.4 (65)	2.10
	0.083	120 (827)	90 (621)	9.3 (64)	2.20
	0.833	118 (814)	93 (641)	9.4 (65)	2.04
	0.000 83	106 (731)	89 (614)	8.7 (60)	1.90
	0.008 3	111 (765)	91 (627)	9.1 (63)	2.00
180 (82)	0.017	111 (765)	92 (634)	9.0 (62)	1.93
	0.083	114 (789)	94 (648)	9.1 (63)	1.99
	0.833	113 (779)	95 (655)	9.2 (63)	1.89
	0.000 83	84 (579)	80 (552)	8.1 (56)	1.34
	0.008 3	94 (648)	83 (572)	8.5 (59)	1.63
250 (121)	0.017	96 (662)	88 (607)	8.3 (57)	1.58
	0.083	97 (669)	88 (607)	8.5 (59)	1.62
	0.833	109 (752)	94 (648)	9.0 (62)	1.83

[a] Data reported are mean values from at least five tests.
[b] UTS, ultimate tensile strength.
[c] TYS, tensile yield strength.

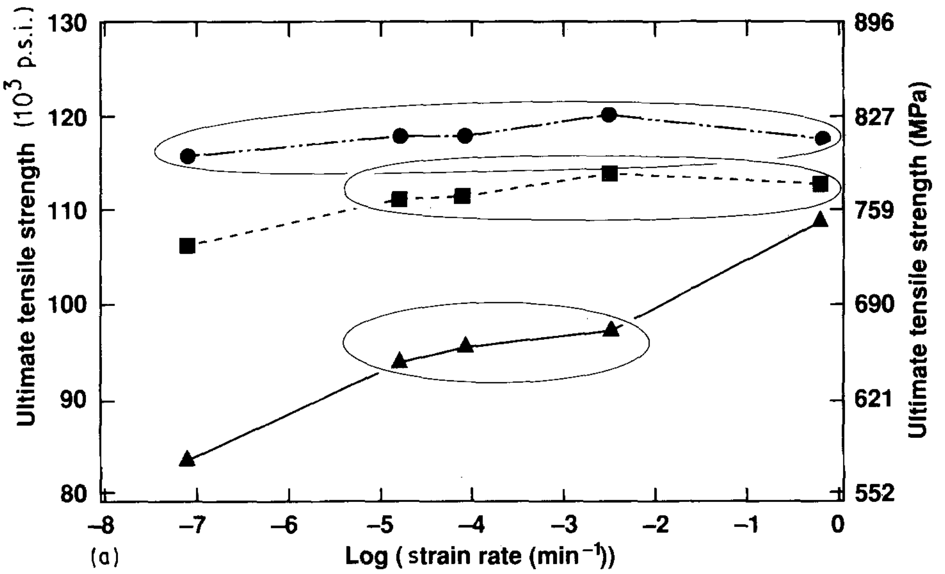


Figure 5a Effect of strain rate on the ultimate tensile strength of 3/2 ARALL-1 laminates at various temperatures. (●) 75 °F; (■) 180 °F; (▲) 250 °F.

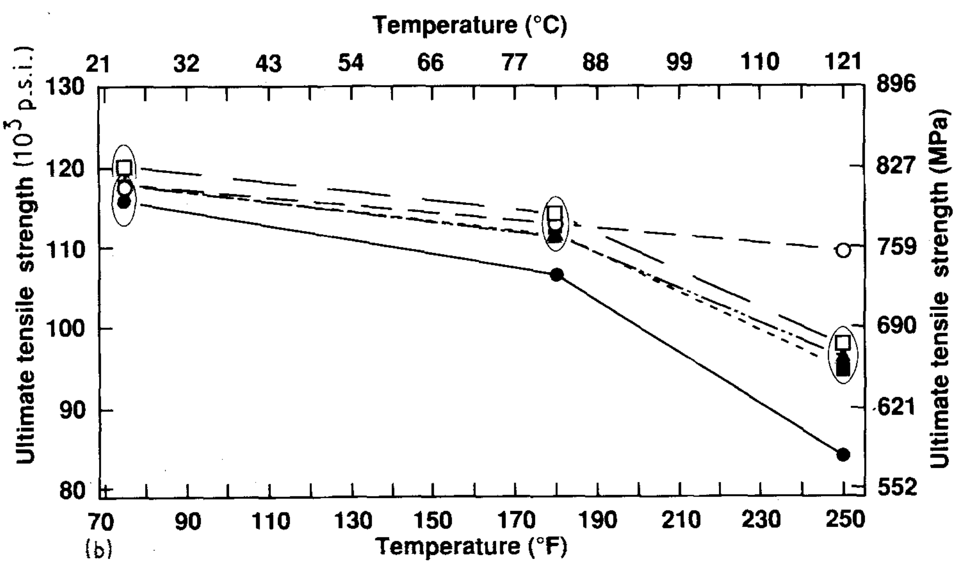


Figure 5b Effect of ultimate tensile strength of 3/2 ARALL-1 laminates at various strain rates. (●) 0.000 83 min^{-1}; (■) 0.0083; (▲) 0.017; (□) 0.083; (○) 0.833.

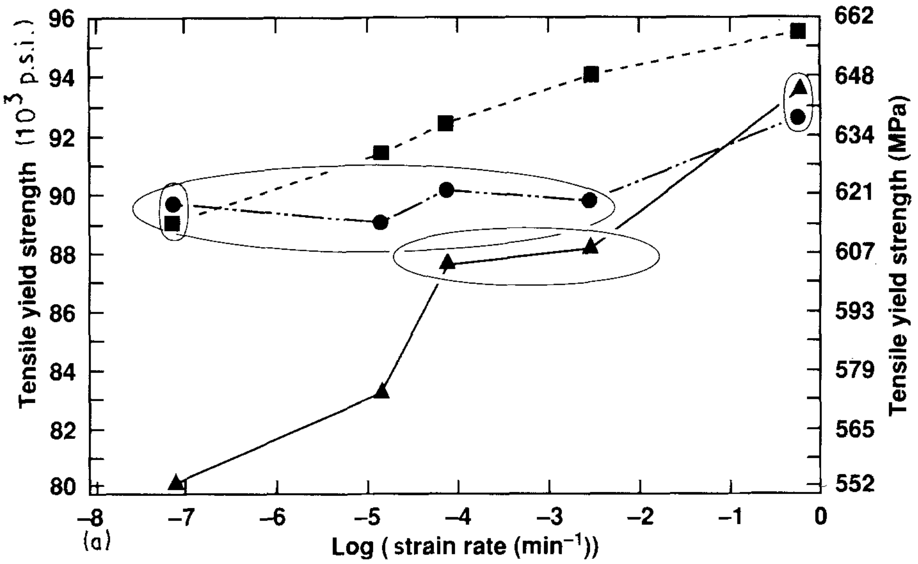


Figure 6a Effect of strain rate on the tensile yield strength of 3/2 ARALL-1 laminates at various temperatures. (●) 75 °F; (■) 180 °F; (▲) 250 °F.

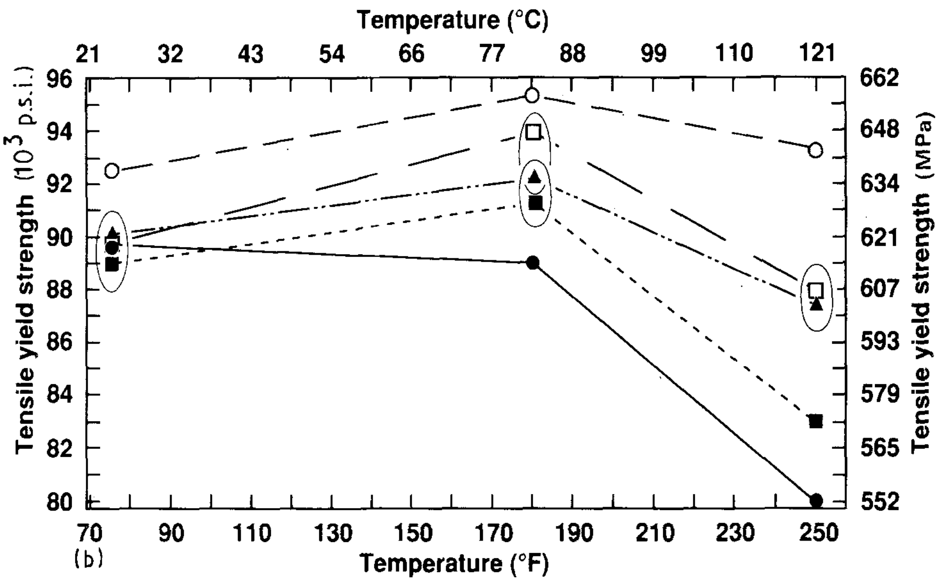


Figure 6b Effect of tensile yield strength of 3/2 ARALL-1 laminates at various strain rates. (—·—) 0.000 83 min^{-1}; (■) 0.0083; (▲) 0.017; (□) 0.083; (○) 0.833.

show the strength averages plotted against strain rate for the various temperatures, while Figs 5b and 6b show the plots of strength averages versus the temperature for the different strain rates. The ellipses in the figures enclose averages which are not judged to be statistically significantly different at the 95% level. Because the lines drawn in the figures are not parallel, there is statistically significant interaction between strain rate and temperature.

Statistical analysis of the ultimate tensile strength at room temperature and 180 °F shows no significant effect of strain rate except at the slowest strain rate at 180 °F. However, the results for 250 °F show that the strain rate has a statistically significant effect at the 95% level. The ultimate tensile strengths of ARALL-1 laminates, Fig. 5a, at low strain rates decreased steadily as the temperature increased, dropping from 116×10^3 p.s.i. (800 MPa) to 106×10^3 p.s.i. (731 MPa) at 180 °F and from 116×10^3 p.s.i. (800 MPa) to 84 $\times 10^3$ p.s.i. at 250 °F. At the highest strain rate, this strength reduction was not as large. The tensile yield strength presented in Fig. 6a, shows an insignificant effect at room temperature, however, the tensile yield strength at 180 and 250 °F decreased as the temperature decreased.

In Figs 7a and 8a the approximate moduli and fracture strains showed no consistent dependence with temperature up to 180 °F, and remained relatively constant over the strain rate range. However, the approximate moduli and fracture strains were significantly affected at 250 °F over various strain rates. In Figs 7b and 8b, the approximate moduli and fracture strains at 250 °F were dependent on strain rate.

3.3. Fracture topography

In the aramid/epoxy layer of ARALL-1 laminates, the progression of matrix disintegration with temperature which causes this deterioration in strength can be followed in Fig. 9. The epoxy resin became discoloured and deteriorated at 250 °F, with only the aramid

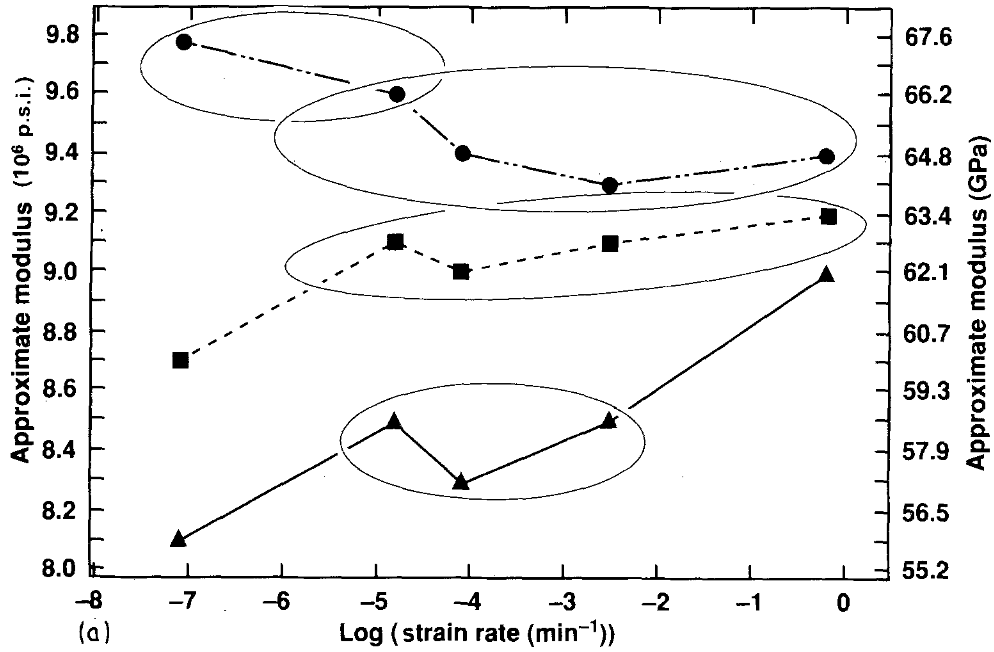


Figure 7a Effect of approximate modulus of 3/2 ARALL-1 laminates on strain rate at various temperatures. (●) 75 °F; (■) 180 °F; (▲) 250 °F.

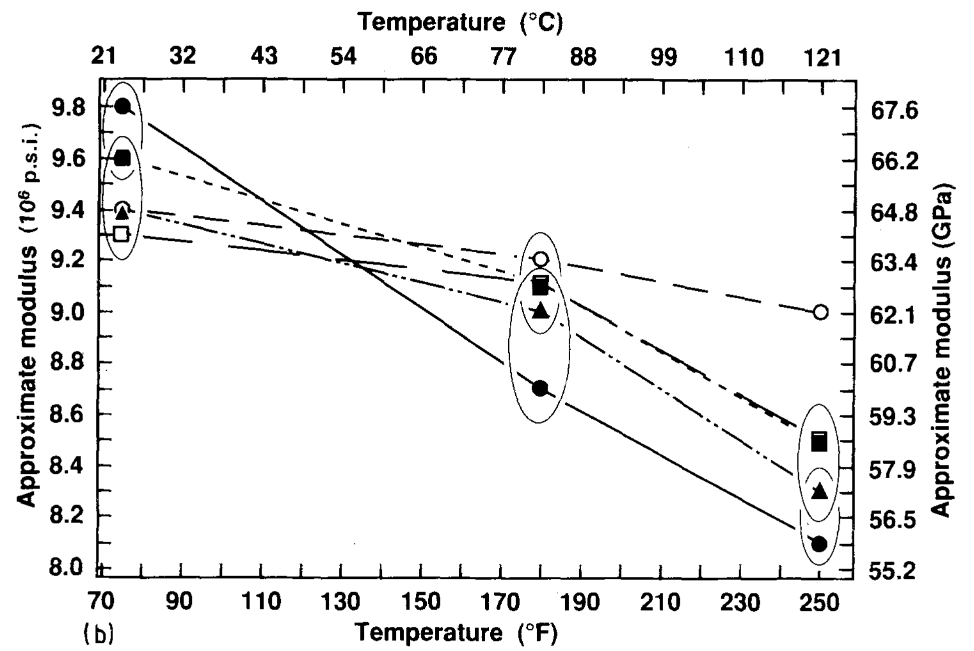


Figure 7b Effect of approximate modulus of 3/2 ARALL-1 laminates at various strain rates. (●) 0.000 83 min^{-1}; (■) 0.0083; (▲) 0.017; (□) 0.083; (○) 0.833.

fibre scrim holding the composite together. This is because the ultimate service temperature of aramid/epoxy composites (AF-163-2U) was 180 °F. The test specimens also were exposed at high temperature (250 °F) for about 30 min. which accelerated the degradation of the cured aramid/epoxy. However, looking at the scanning electron photomicrographs in Fig. 10, due to the fast loading of the high strain rate (0.833 min^{-1}), no such significant degradation of fracture surfaces was clearly observed at three different temperatures. In general, at temperatures above ambient, the strength was somewhat higher at high strain rates than at low strain rates. These observations once again confirm that ARALL-1 laminates are good for elevated temperature applications up to 180 °F.

4. Conclusions

The tensile properties of ARALL-1 laminates were studied as a function of temperature and strain rate. At room temperature (75 °F) and 180 °F, ultimate tensile strength, approximate modulus, and fracture strain were not sensitive to the strain rate, while at 250 °F, the sensitivity of these properties to strain rate was very obvious. It was also observed that the tensile yield strength decreased as the strain rate decreased.

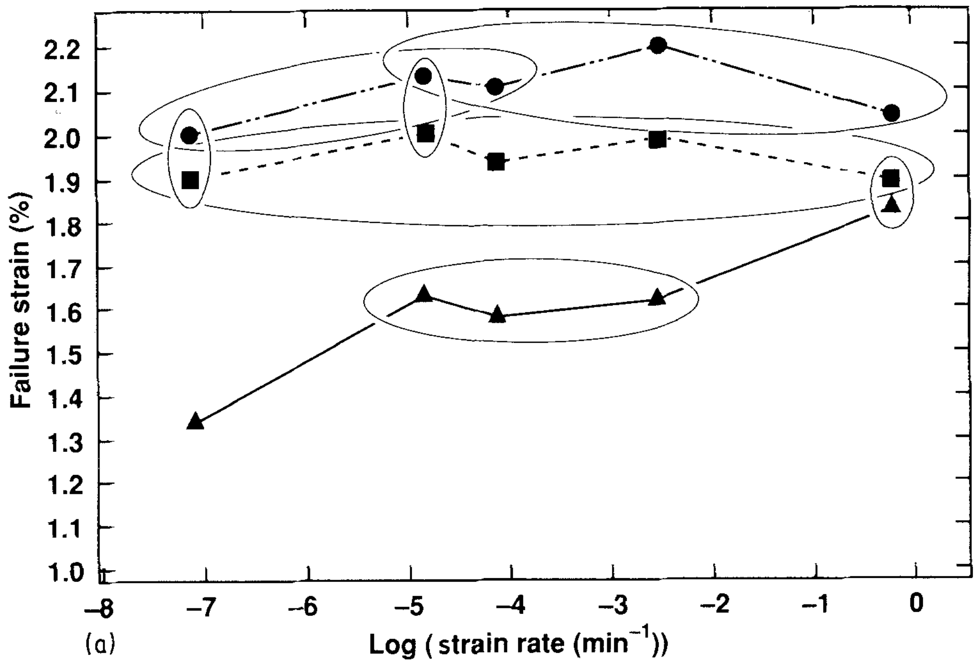


Figure 8a Effect of failure strain of 3/2 ARALL-1 laminates on strain rate at various temperatures. (●) 75 °F; (■) 180 °F; (▲) 250 °F

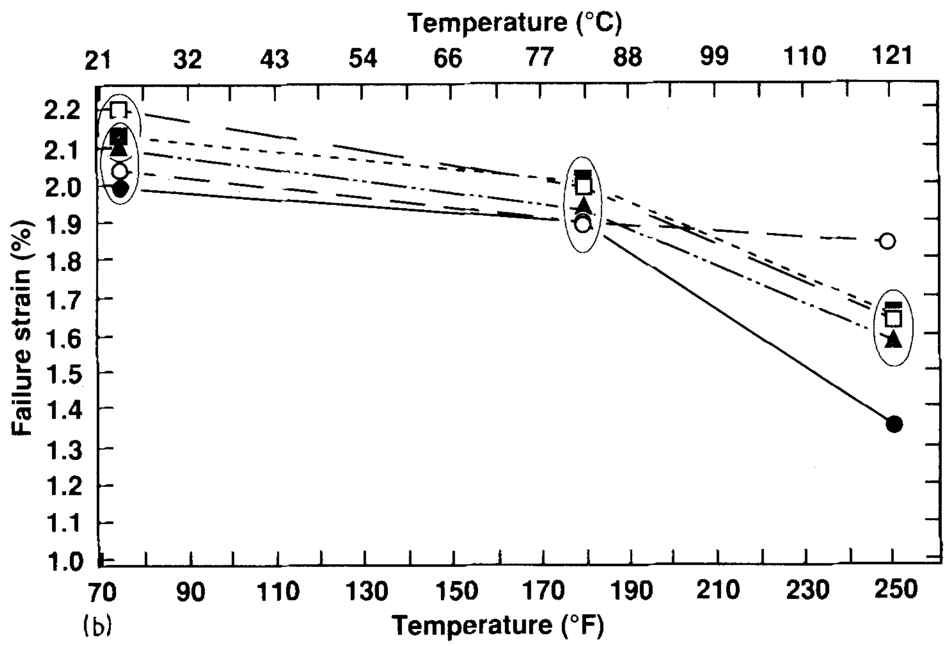
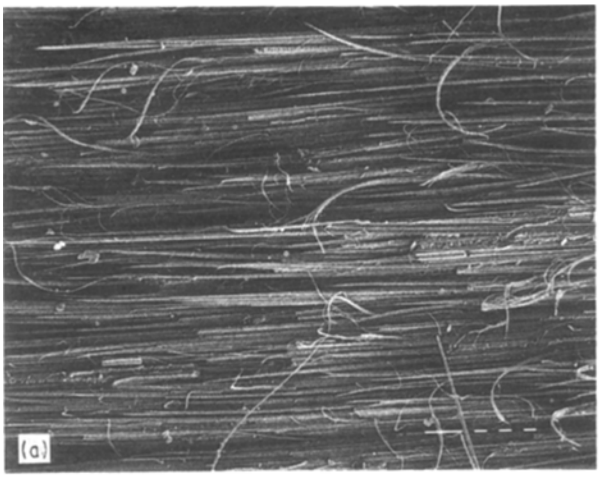


Figure 8b Effect of failure strain of 3/2 ARALL-1 laminates at various strain rates. (●) 0.000 83 min^{-1}; (■) 0.0083; (▲) 0.017; (□) 0.083; (○) 0.833.

The tensile properties were moderately reduced at high temperatures and were higher at high strain rates than at low strain rates. The reduction of temperature and strain rate effects to design applications will require more complex test programmes and a better understanding of the basis for these combined effects. It is encouraging to note that high strain rate loading does not cause much deterioration of tensile properties, and tends to push up the temperature barrier to some extent. In conclusion, the temperature effect is more significant than that due to strain rate.

Scanning electron photomicrographs in the aramid/epoxy layer of ARALL-1 laminates show that the fracture surface does not change at the highest strain rate of the three temperatures investigated. However, a significant difference in fracture appeared at the lowest strain rate over the temperature range. This indicates that ARALL-1 laminates are suitable for



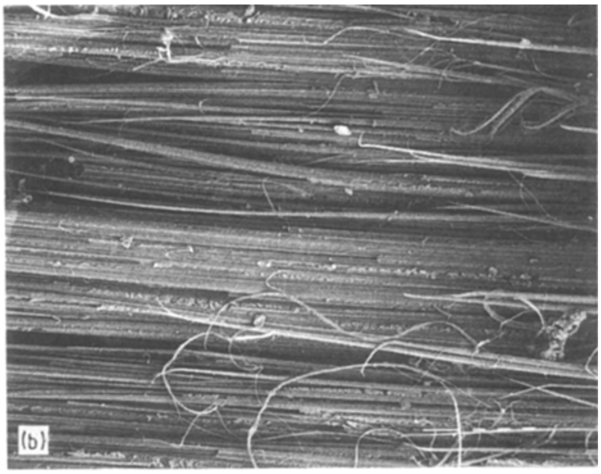
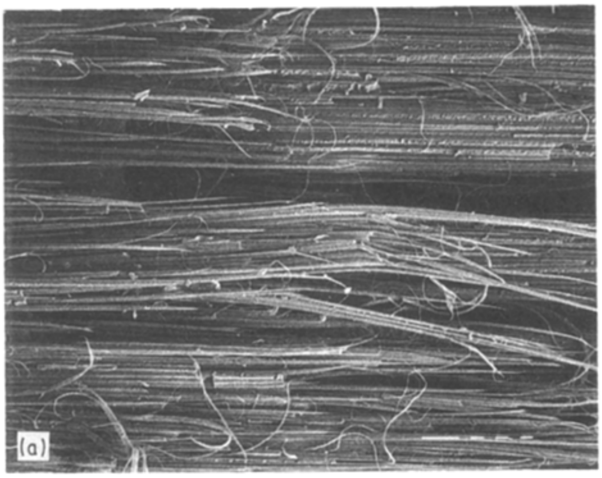


Figure 9 Scanning electron photomicrographs of the fracture surface in the aramid/epoxy layer of ARALL-1 laminates tested at the lowest strain rate (0.000 83 min^{-1}) and in the temperature range (a) 75 °F (24 °C), (b) 180 °F (82 °C), and (c) 250 °F (121 °C) × 100.



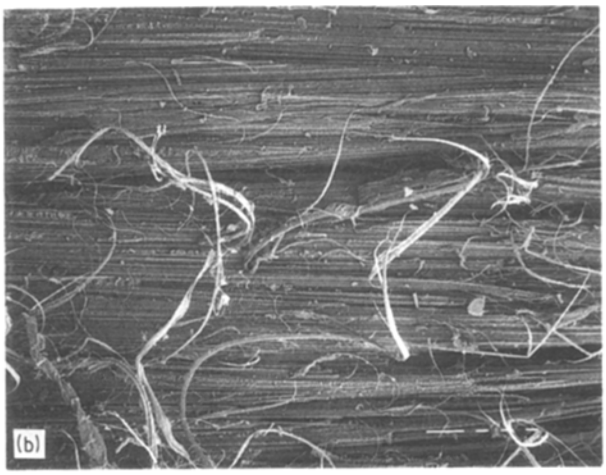


Figure 10 Scanning electron photomicrographs of the fracture surface in the aramid/epoxy layer of ARALL-1 laminates tested at the highest strain rate (0.833 min^{-1}) and in the temperature range (a) 75 °F (24 °C), (b) 180 °F (82 °C), and (c) 250 °F (121 °C) × 100.

applications up to 180 °F. For service temperature up to 250 °F, the ARALL-4 laminates [10] are recommended.

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