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Preparation and characterization of aluminium alloy sheet Aramid fibre-laminated composites

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Abstract. Laminated composites consisting of alternate layers of aluminium alloy sheets and unidirectional Kevlar-49 fibre epoxy composites were prepared using two different aluminium alloys DTD 687 and aluminium-lithium alloy. Tensile, compressive and interlaminar shear strengths of the laminates were measured. The residual stresses in the aluminium alloy sheets arising out of thermal mismatch between aluminium alloys and aramid fibres were also measured. It is found that the laminates have lower density, higher tensile strength and marginally lower Young's modulus as compared with monolithic alloy sheets.

Keywords. Aluminium alloy; laminated composites; aramid fibres; tensile strength; compressive strength; interlaminar shear strength; residual stresses.

1. Introduction

The aluminium alloy-aramid laminate is a hybrid composite obtained by adhesive bonding of aluminium alloy sheets with unidirectional aramid fibre-epoxy composite. This material, commonly known as Arall (Aramid fibre reinforced aluminium laminate) has a substantially lower density and higher tensile strength compared with those of monolithic aluminium alloys used in the laminate. The most important property of Arall is its ability to reduce the fatigue crack propagation rates (Vogelsang *et al* 1981; Vogelsang and Gunnink 1983; Marissen 1984; Davis 1985; Roebroeks and Intvelt 1986). The rates of fatigue crack propagation in these materials show a marked insensitivity to the stress intensity factor (Vogelsang *et al* 1981; Marissen 1984). Further, the Arall laminates can be shaped to different contours by conventional sheet metal shaping techniques (Vogelsang and Gunnink 1983). Because of these attractive properties this material is aptly projected as the material for the next generation aircraft.

The present paper describes the preparation and characterization of aluminium alloy-aramid fibre-laminated composites. The static mechanical properties and the resistance to environmental degradation have been evaluated. The residual stresses in the aluminium alloy sheets, which arise due to the fact that the coefficients of thermal expansion of aluminium alloy sheet and the aramid fibres are different and that the laminates are processed at elevated temperature, have been measured by X-ray diffraction techniques.

2. Experimental details

2.1 *Preparation of the laminates*

The choice of resin system and the surface treatment of the aluminium alloy sheet are important steps in the fabrication of these laminates. The resin system should have high toughness to impart good interlaminar shear strength to the laminate. The resin should also have a suitable melt rheology for proper impregnation and controlling the resin content in the aramid epoxy layer during fabrication of the laminates. The latter aspect is especially important because only edge-bleeding is possible during laminate fabrication due to the presence of aluminium alloy face sheets. The surface treatments given to the aluminium alloy sheets, including the primer application, should promote good adhesive bonding with the resin.

In this study, two sets of laminates were prepared, one with aluminium–zinc alloy (DTD-687) and the other with aluminium-lithium alloy (Lital-A). The aluminium alloy sheets ($300 \times 300 \times 0{\cdot}5\ \text{mm}^3$) were cleaned with a liquid detergent and degreased using trichloroethylene. The degreased sheets were etched in 14% aqueous sodium hydroxide solution for 10 min at 250°C followed by an FPL etch (chromic acid-sulphuric acid mixture) for 2 min at 70°C. The etched sheets were thoroughly washed in running water and dried at 80°C for 1 h in an oven. A specially formulated epoxy primer was applied on the dried sheets.

The prepregs of Kevlar 49 and epoxy (formulated inhouse) were prepared by hand-winding a 4500 den Kevlar 49 yarn on a steel plate and by applying the resin with a brush. The wet prepregs were brought to B-stage of curing by keeping the prepregs at 100°C for 30 min.

The laminates were prepared by stacking the surface-treated alloy sheets and the prepregs to form a lay-up with two face sheets of the aluminium alloy sandwiching the Kevlar-epoxy prepreg. The laminate was then cured in a press at 135°C under a 200 kPa pressure. The volume fraction of aramid-epoxy core was maintained between 0·3 and 0·35. The resin content of the Kevlar-epoxy layer was maintained at $50 \pm 2\%$ by volume.

2.2 *Mechanical testing*

Tensile test specimens were prepared by cutting the laminate into 25 mm × 200 mm strips. Tapered aluminium end tabs (50 mm long) were adhesively bonded to the specimens at the grip-portion of the specimens, leaving a gauge length of 100 mm. The tests were then conducted on an Instron 1175 universal testing machine. A strain gauge extensometer (50 mm gauge length) mounted on the specimens was used to measure elongation. The load-elongation plot was recorded on an X–Y recorder. Tensile strength and tensile modulus were calculated from this plot (ASTM-D3039). Compressive strengths were measured (ASTM D3410-75) on 6 mm × 62·5 mm specimens using a face loading type fixture. The gauge length of the specimen was 12·5 mm. Flexural strengths were measured (ASTM-D790) by the three-point bending method with a span-to-thickness ratio of 32.

The interlaminar shear strengths were measured by the short beam shear method. The span-to-thickness ratio was 5. To calculate the shear strengths, the values obtained on only those specimens which failed in shear were considered.

The environmental resistance of the laminates were tested according to MIL specifications (MIL-A-25463 and MIL-A-9067C) in DTD 687-Kevlar 49-epoxy laminates. Flexural test specimens were exposed to water at room temperature, boiling water and 80°C for specified periods of time. The flexural strengths of the exposed specimens were then determined. Flexural tests were also conducted at 60°C and 80°C.

2.3 *Residual stress measurement*

The residual stresses were measured by X-ray diffraction technique (Cullity 1978; Taylor 1961) and the strain gauge method (SAE 1965). A Norelco powder diffractometer along with a PW 1390 channel control unit and PW 1140 X-ray generator was used to record the diffraction data. The specimen shaft of the diffractometer was modified to set the inclination angle. The radiation used was CuK$_\alpha$. Since the sensitivity of stress measurement increases with increasing Bragg angle, the (511, 333) reflections of aluminium were used. The region around the peak was scanned at 0·05° 2θ intervals in fixed time count mode and the peak position determined by fitting a parabola through the data by the least-squares method. The measurements were conducted at inclination angles of 0°, 20°, 30°, 40° and 45°. The stresses were measured both parallel and perpendicular to the fibre direction.

In the strain gauge method, strain gauges were fixed on the aluminium layer on one side of the laminate in the direction of the fibres and perpendicular to the fibres. The aluminium layer and the aramid layers were removed from the other side. The change in strain indicated by the strain gauges at the end of the layer removal was used to compute the residual stresses.

3. Results and discussion

A typical stress strain curve for the laminates along with that for the monolithic aluminium alloy is shown in figure 1. It is seen that even after the aluminium alloy sheets yield, the laminate maintains a reasonable stiffness. The slope of the stress strain curve in the post-yielding region is about 25 GPa which is approximately 36% of the initial modulus.

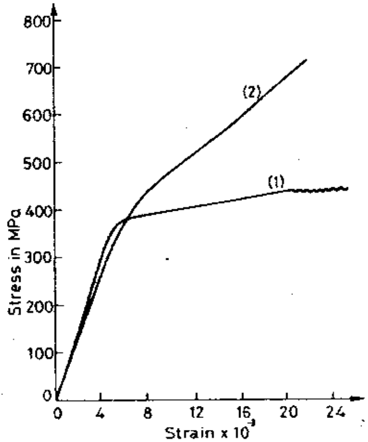

Figure 1. Stress strain curves for (1) DTD 687 aluminium alloy and (2) 687 aluminium alloy aramid fibre laminate.

The tensile and compressive properties of the laminates are given in table 1. The tensile strengths of the laminates are 670 MPa and 655 MPa for laminates with Lital A and DTD 687 alloys respectively. These values are about 30 and 40% higher than the strengths of the corresponding alloys.

The tensile strength, σ_L, of such laminates is given in terms of the tensile strengths, σ_A and σ_K of the aluminium alloy sheet and Kevlar-epoxy composite respectively by the additive rule of mixtures,

$$\sigma_L = V_A \sigma_A \times V_K \sigma_K \tag{1}$$

where V_A and V_K are the volume fractions of aluminium alloy and Kevlar-epoxy composite respectively. Taking $\sigma_K = 1020$ MPa for 50% volume fraction of Kevlar in Kevlar-epoxy composite, $\sigma_A = 470$ MPa for DTD 687 and $\sigma_A = 510$ MPa for Lital A and $V_K = (1 - V_A) = 0{\cdot}35$, equation (1) gives $\sigma_L = 662$ MPa for DTD 687 and $\sigma_L = 688$ MPa for Lital-A laminate. These values are in reasonable agreement with the experimentally observed values for the corresponding laminates (table 1).

The compressive strength of aramid fibre-epoxy composite is 276 MPa. A corresponding decrease in the compressive strength of the laminate as compared with that of the alloy sheet is observed (table 1). The interlaminar shear strengths (ILSS) of the laminates are given in table 2. It may be noted that the ILSS values of the laminates

Table 1. Mechanical properties of alloy sheets, composite and laminates

Material	Tensile strength (MPa)	Standard deviation (MPa)	Tensile modulus (GPa)	Standard deviation (GPa)	Compressive strength (MPa)	Standard deviation (MPa)	Density (g/cc)
DTD-687 [‡] alloy	470	–	69·6	–	380	–	2·71
DTD-687 Kevlar 49 laminate	655	33	67·5	2·8	312	23	2·23
Al-Li alloy [‡] (Lital A)	510	–	72.5	–	420	–	2·51
Al-Li alloy Kevlar 49 laminates	670	41	69·0	2·6	385	28	2·12
Kevlar 49/epoxy	1020	52	61·0	3·1	276	15	1·35

[‡] The properties of the alloys are taken from literature

Table 2. Flexure and shear properties of laminates

	Flexural strength (MPa)	Standard deviation (MPa)	Interlaminar shear strength (MPa)	Standard deviation (MPa)
DTD 687–Kevlar 49 (3 layers)	870	48·7	48·6	4·3
Li-Al-Kevlar 49 (3 layers)	910	55·5	53·4	3·8
Kevlar 49-epoxy	1320	92·4	52·0	4·7

The failure was in the aramid fibre layer and not at the alloy-fibre layer interface

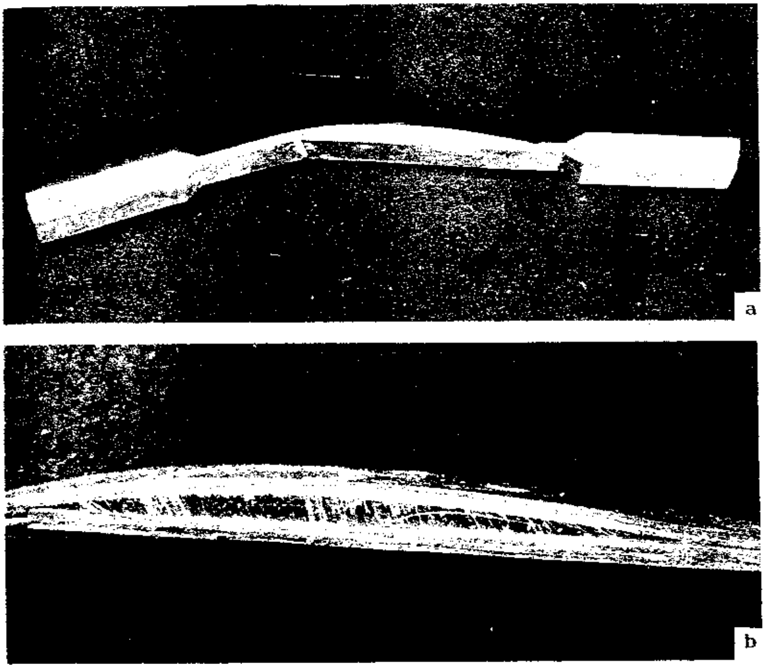

Figure 2. **a.** Photograph of a failed tensile specimen of DTD 687/aramid laminate. **b.** Close-up view of a failed tensile specimen showing fibre bridging. Note that the failure is in the composite layer and not at the aluminium composite interface.

are close to that of the Kevlar 49-epoxy composite. The flexural strengths of the laminates are also listed in table 2.

Figure 2 shows a photograph of a failed tensile specimen. It can be seen that the failure took place in the aluminium alloy face sheet. The fibres bridging the failed aluminium alloy sheets can be clearly seen in the photograph. These factors clearly show that the bonding between the aluminium alloy sheets and the aramid layer is very good and does not give rise to delamination during tensile failure.

Further evidence for good bonding can be had from the analysis of the stress-strain curve in figure 1. It was noticed that the tensile failure of the laminate did not give rise to localized plastic deformation (necking) in the aluminium alloy sheets. The plastic deformation was uniform throughout the gauge length of the specimens and the total elongation to failure was 2% compared to the failure elongation of 11% for DTD 687 alloy and 5·6% for aluminium lithium alloy respectively. This shows that the laminates behave as true well-bonded composites and not as physical assemblage of the aluminium alloy sheets and the aramid/epoxy layer.

The results of the environmental tests according to the MIL specifications are given in table 3. It is seen that the immersion of the specimens in water and boiling

Table 3. Results of environmental tests on three-layer DTD 687–Kevlar 49 laminates

Conditions for testing	% weight gain	Flexural strength (MPa)	Standard deviation (%)
Ambient temperature		850	5·6
Immersion in water at room temperature for 96 h (tested immediately after removal from water) MIL-A-25463	0·09	892	2·9
Immersion in water at room temperature for 96 h (tested after drying at room temperature for 72 h and at 50°C for 2 h) MIL-A-25463	−0·028	873	3·1
Immersion in boiling water for 24 hours (tested after drying at room temperature for 65 h and at 50°C for 2 h) MIL-A-9067C	0·33	878	4·2
Heating for 75 h at 80°C (tested after 72 h at RT) MIL-A-25463	—	876	4·5
Tested at 60°C	—	843	4·6
Tested at 80°C	—	399	2·8

Table 4. Residual stresses in DTD 687 Kevlar fibre laminates

Method	Surface	$\sigma_\parallel$ (in MPa)	$\sigma_\perp$ (MPa)
X-ray diffraction	A	23	−9
	B	25	−3
Strain gauge method	A	27	−12

water does not result in a drop in room temperature flexural strengths. However, the shear strength at 80°C is about half the value at room temperature. A high temperature resin system is being developed to overcome this problem.

The results of the residual stress measurements are given in table 4. The presence of a residual tensile stress in the alloy sheets, of about 25–30 MPa along the fibre direction and residual compressive stress of about 12–15 MPa perpendicular to the fibres was found (Balasingh *et al* 1989). The results obtained by X-ray diffraction method agree well with those obtained by the strain gauge method. However, the tensile surface residual stresses are not desirable from the point of view of fatigue crack initiation. Hence, these laminates should be subjected to some treatment, like stretching, to reduce the tensile residual stresses. It is preferable to have compressive surface residual stresses.

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