JOURNAL OF MATERIALS SCIENCE 25 (1990) 4957–4964

Strength and fracture behaviour of diffusion-bonded joints in Al–Li (8090) alloy

Part 1 *Shear strength*

D. V. DUNFORD, P. G. PARTRIDGE
Materials and Structures Department, Royal Aerospace Establishment, Farnborough, Hampshire, UK

The shear strength (τ) of overlap shear test pieces made by solid state diffusion bonding or by machining thin (2.5 or 4 mm thick) Al–Li 8090 alloy sheet has been determined for various overlap lengths (l). When $l < 3$ mm, τ was independent of l and equal to 188 to 202 MPa for the bonded joint and 199 to 209 MPa for the base metal sheet. The lower mean shear strength of the bonded joint was caused by the lower resistance of intergranular fracture in the planar grain boundary at the bond interface. The bond strengths were, however, greater than those previously reported for joints in 8090 alloy made by solid-state or liquid-phase diffusion bonding and about a factor of 7 greater than those for adhesive bonded joints.

1. Introduction

Superplastic forming (SPF) has become an established manufacturing process for titanium and aluminium alloy sheet components [1] and when combined with diffusion bonding (SPF/DB) substantial cost and weight savings can be achieved in titanium aerospace structures compared with conventional riveted titanium structures [2]. Diffusion bonding (DB) is more difficult for aluminium alloys because of their stable surface oxide film [3–5]. Some bond strength data have shown unacceptably large scatter and low minimum values [6] whilst other data [7, 8] indicate that bond shear strengths equal to that of the base metal can be obtained. The major causes of scatter in the measured bond shear strength values for thin sheet are prior bond interface contamination [3–5] and peel stresses arising from bending of the overlap shear test piece [9]. The low density and high specific strengths associated with aluminium–lithium alloys [10] make them particularly attractive for SPF/DB processing. However, lithium-containing alloys oxidize more readily than lithium-free alloys [11] and are reported to be more difficult to diffusion bond [12, 13].

Published strength data on diffusion-bonded Al–Li alloy joints are summarized in Table I [4, 13–15]. Following experiments on clad Al–Li alloy sheet [4] further studies have been carried out on the solid-state diffusion bonding of unclad commercial Al–Li 8090 alloy sheet. In Part 1 of this paper the bonding technique and shear strength data are presented. The bond fracture behaviour and peel strength data are described in Parts 2 and 3, respectively [16, 17].

2. Experimental procedure

Al–Li 8090 alloy sheet with a composition (wt %) of Al–2.5% Li–1.3% Cu–0.8% Mg–0.12% Zr–0.1% Fe–0.05% Si was used in thicknesses of 2.5 and 4 mm.

Two types of overlap shear test pieces were used. Type 1 test piece blanks were 30 mm × 25 mm with an overlap length (l) of ~5 mm and were bonded in a jig described elsewhere [18]. Type 2 test pieces consisted of two blanks 75 mm × 25 mm and 55 mm × 25 mm (Fig. 1a). At the centre of the smaller blank a 15 mm long step 0.3 to 0.5 mm high was machined to provide accurate control of area and deformation during bonding. Surfaces to be bonded were mechanically polished to 1 μm diamond or 1200 grit finish in a direction parallel (L) or perpendicular (T) to the tensile shear axis.

Diffusion bonding was carried out in a hot press by bonding two sheets of identical thickness under platen pressure at predetermined conditions of temperature and pressure to give a final overall through thickness deformation of 6% to 12%. After bonding and heat treatment, surface slots were cut to the depth of the bond line in Type 2 test pieces to give overlap lengths, l, of 1.9 to 15.1 mm. A 5 mm wide section was sometimes cut from each edge of the bonded test pieces to determine the microstructure before and after heat treatment. The heat treatment consisted of either a solution heat treatment (SHT) of 20 min at 530° C followed by a water quench or an SHT + age treatment (STA), where the ageing consisted of 5 h at 185° C followed by an air cool. Bond shear tests were carried out in a shear test jig described elsewhere [18].

Tensile properties of the base metal sheet were determined after re-heat treatment to the STA condition or after a vacuum thermal cycle (TC) of 1 to 4 h at 560° C, to simulate the bonding cycle, followed either by SHT or STA treatments. The shear strength of the base metal sheet was obtained by making a Type 2 test piece from 4 mm thick sheet by cutting surface slots 6 mm wide to a depth of 2 mm to give overlap lengths, l, in the range 2 to 5.3 mm. The shear

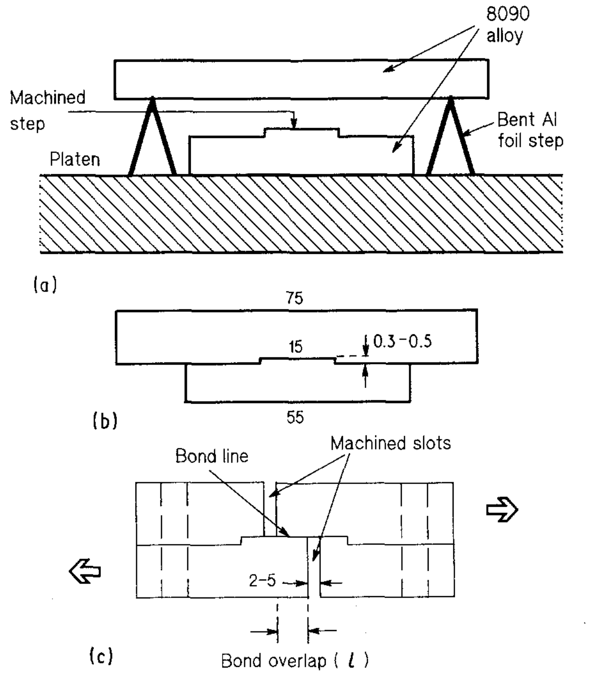


Figure 1 Schematic diagram of shear test piece Type 2, (a) before bonding, (b) after bonding, (c) before testing. Number denote dimensions in mm.

tests were carried out on sheet in the TC + SHT and STA conditions.

Slotted shear test pieces (similar to Type 2 without the step) are widely used for testing diffusion-bonded aluminium-alloy joints. In practice the bottom of the machined slot is sometimes above or below the bond plane by a small distance, *h*; in the current tests *h* was in the range 0.1 to 0.2 mm. This leads to three types of slot (numbered 1 to 3 in Fig. 2) and five possible slot combinations for a shear test piece. The ideal combination 1/1 (Fig. 2a) has the base of the slots at the bond plane; in all other combinations one or both slots are above or below the bond plane. Only in combination 2/3 (Fig. 2b) can shear between the base of the notches occur without intercepting the bond plane.

3. Results

3.1. Microstructure of diffusion-bonded joints

The characteristic microstructure of unrecrystallized and partially recrystallized sheet after DB and re-heat treatment to the STA condition is shown in Figs 3 to 5. In the unrecrystallized sheet the grain diameter in the ST direction was 2 to 8 μm compared with 10 to 40 μm in the L direction (Fig. 3) and it was difficult to distinguish the planar grain-boundary interface from similar planar boundaries aligned in the L direction in the base metal. A slightly rougher bond interface was obtained for sheet with a 1200 SiC grit surface finish (Fig. 4). In partially recrystallized sheet the grain boundaries of the flattened surface grains remained pinned in the planar bond interface (Fig. 5). These microstructures show that the thermo-mechanical working associated with diffusion bonding and the subsequent heat treatment failed to cause grain-boundary migration across the bond interface.

3.2. Shear strength of diffusion-bonded joints

Test pieces in the re-solution heat-treated condition either failed in tension in the base metal or became so

TABLE I Shear strengths of diffusion-bonded 8090 Al–Li alloy

Bonding technique	Sheet thickness, *t*, and surface finish	Overlap length, *l* (mm)	Environment	Bonding conditions	Post-bond heat treatment	Shear stress, τ MPa	Reference
Hot platen. Clad silver-coated sheet. Solid state.	t = 1.8 mm 1 μm diamond polish	3.6 ($2t$)	Air/argon	280–300° C 100–130 MPa 45 min 10% deformation	16 h, 530° C, WQ (SHT) + 5 h 185° C (STA)	104 (SHT) 98 (STA)	[4]
Hot platen. Clad sheet with or without silver coating. Solid state.	t = 3.5 mm 1200 SiC grit ground surface or 1 μm diamond polish	6 ($\sim 2t$)	Air/argon	538 ± 5° C 50 MPa (max) 0.5–5.8 h above 500° C	24 h 530° C	34–110 (1200 grit, no silver) 50–56 (1 μm diamond, no silver) 0–60 (1 μm diamond, silver)	[13]
Induction heating. Solid state.	$t \sim 3$ mm 180 SiC grit ground surface	$\sim$3 ($1t$)	Vacuum $< 10^{-2}$ Pa	525° C 2.5 MPa 40 min 10% (max) deformation		125–175	[14]
Hot platen. Zn–1% Cu clad layer. Liquid phase.		1.5	Air or air/argon	500–540° C $\sim$5 MPa 1 h		100–160	[15]
Hot platen. Solid state.	t = 4 mm 1 μm diamond polish	2 ($0.5t$)			20 min, 530° C +5 h, 185° C	181–202	Present results

TABLE II Shear strength of diffusion-bonded joints between 2.5 mm thick 8090 alloy sheet*

Test piece type	Overlap, l (mm)	Bonding time at 560° C (h)	Deformation (%)	Shear stress, τ (MPa)	Failure load normalized to 11 mm width (kN)
1	4.4	4	5.3	118	5.7
1	4.7	1	3.9	119	5.7
1†	5.0	1		126	7.1
2	5.1	4	4.8	99	6.4
2	5.2	19	6.1	110	6.3

*Orientation, Type 1 test piece, re-heat treated to STA condition.
†Surface finish 1200 SiC grit.

severely bent that a valid shear test could not be carried out.

All bonded joints re-heat treated to the STA condition fractured in the bond interface. The shear strengths (τ) are shown in Table II and III and the data are plotted in Fig. 6. A plateau in the τ–l curve was obtained for values less than 3 mm; for $l > 3$ mm the shear strength decreased with increase in l and increased bending of the test piece was observed. This agrees with previous results [9] which showed a change from almost pure shear in the plateau region to mixed shear and tension (peel) beyond the plateau region.

The transition from shear to peel was apparent at low magnification in the fracture surfaces. In the plateau region the fracture appeared uniform over the whole fracture surface as shown in Fig. 7a. Beyond the plateau region fracture surfaces exhibited two distinct fracture zones. Zone 1 at the ends of the fracture (at A in Figs 7b and c) formed first during the shear test and was associated predominantly with tensile-type fracture. Zone 2, between zones 1 (at B in Figs 7b and c) was associated with mixed shear and tensile-type fracture and was the last part of the bond interface to fracture.

The shear stress for the plateau region was 191 ± 8 MPa with measured shear strengths in the range 181 to 202 MPa. No significant effect on the shear strength of test piece type, sheet thickness or bonding time (1 to 19 h) was apparent, but higher shear strength was obtained for the test piece with the 1200 SiC grit surface finish (Fig. 6).

The deformation occurring during a shear test of a bonded joint was revealed in polished edge faces of a shear test piece (Fig. 8); extensive deformation occurred in the base metal to a distance of 0.4 to 0.8 mm either side of the bond plane. When the slot depth was type 2 or 3 (Fig. 2) intergranular cracks were often visible in the base metal at the corner of the slot (at B in Fig. 9) after shear fracture in the bond plane at A–A. These results indicate that the diffusion bond had a strength very close or equal to that of the base metal.

The other important feature of the bond failure was the planarity of the fracture surface, e.g. at A–A in Fig. 9. The fracture surface at very high magnification showed some evidence of plastic deformation but followed closely the planar grain boundaries that formed at the bond interface (Figs 3 to 5). A more detailed description of the diffusion bond fracture will be given in Part 2 [16].

3.3. Shear and tensile strength of 8090 alloy sheets

The tensile properties of the 8090 sheets (2.5 and 4 mm thick) determined after re-heat treatment to various conditions are given in Table IV. The two thermal cycles of 1 and 4 h at 560° C reduced the strengths by 6% to 7% (0.2% proof stress) and 9% to 10% (tensile strength). Much lower strengths were obtained for the SHT condition.

TABLE III Shear strength of diffusion-bonded joints between 4 mm thick 8090 alloy sheet*

Test piece direction	Overlap, l (mm)	Shear stress, τ (MPa)	Failure load normalized to 11 mm width (kN)
L	1.9	184	3.9
L	2	202	4.5
T	2	193	4.3
T	2	181	4.0
T	2.1	181	4.1
T	2.1	197	4.5
L	2.1	199	4.7
L	3.0	177	5.8
L	3.1	184	6.1
L	3.9	116	5.0
L	4.9	119	6.5
L	15.1	67	11.1

*Type 2 test piece, bonding time 4 h, 560° C, deformation 8% to 12% reheat-treated to STA conditions.

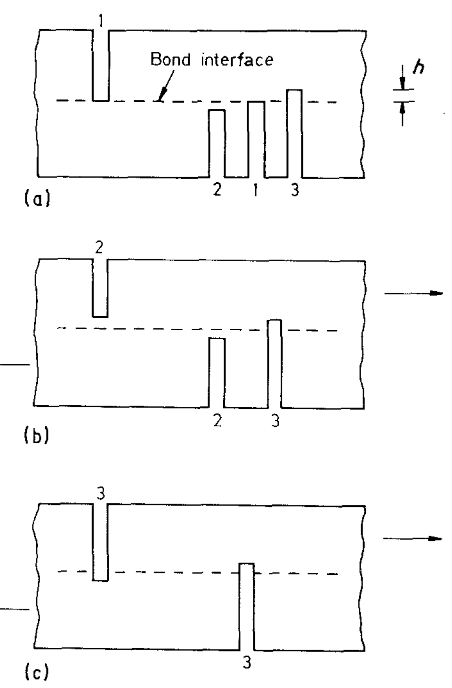


Figure 2 Slot combinations in Type 2 test piece.

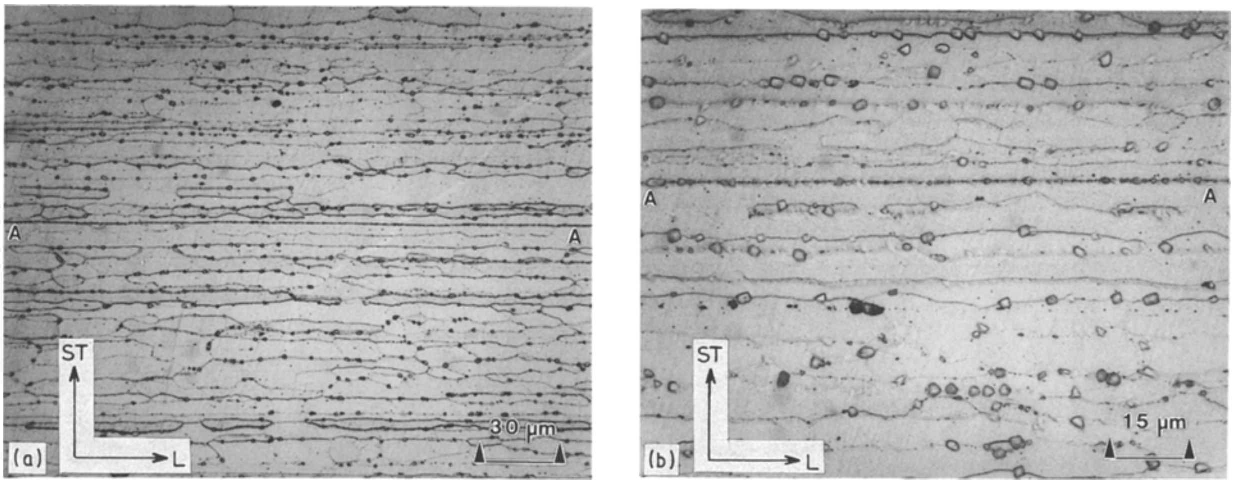


Figure 3 Section through DB joint in unrecrystallized 2.5 mm thick sheet. Surfaces 1 μm diamond polished. Bond interface A–A.

To compare the strength of diffusion-bonded joints with the shear strength of the base metal in the equivalent heat-treated condition, Type 2 test pieces without the step were machined from the 4 mm sheet. The failure stresses and loads are given in Table V. The low strength in the SHT condition led to excessive bending followed by cracking and fracture at the corners of the slots (Fig. 10a) and shear fracture could not be obtained in this condition.

The bending was much less and shear fractures were obtained for sheet in the TC + STA condition (Fig. 10b). Tensile fracture occurred through the 2 mm net section at the two largest overlaps of 3.9 and 5.3 mm; the ratio of tensile strength in the presence of a slot to the tensile strength of the base metal was 0.66. The shear stress–overlap length (τ–l) curve (Fig. 11) was similar to the curve for the diffusion-bonded joint (Fig. 6) but the plateau occurred at 203 $\pm$ 4 MPa with shear strengths in the range 199 to 209 MPa. The mean plateau stress for the base metal was 12 MPa greater than for the diffusion-bonded joint.

Although the shear fracture surface was less planar overall than for the diffusion-bonded joint, the intergranular fracture mode was dominant in the base metal shear fracture as shown in Fig. 12. Planar fracture regions occurred where the original boundaries were planar, e.g. at A in Fig. 12.

4. Discussion

The present results confirm previous tests [9] indicating that valid shear strength values are only obtained in the plateau region of the curve of shear strength against overlap length. The reduced sensitivity to overlap length and the presence of only Zone 1 fracture in the plateau region may be a consequence of the greater uniformity in the normal (peel) and shear stresses [19, 20] at these short overlap lengths.

The bond shear strength values of 181 to 202 MPa obtained for the 8090 alloy in the plateau region (Table III) are comparable to the corresponding values of 199 to 209 MPa obtained for the base metal (Table V). The bond strengths in the plateau region are greater than any previously reported for Al–Li alloys bonded in either the solid or liquid states (Table I) and about a factor of 7 greater than the strength of adhesive-bonded Al–Li alloy joints [21]. The results indicate that the presence of lithium in aluminium alloys makes solid state diffusion bonding easier and not more difficult as reported elsewhere [12]. The improved bondability is probably caused by the high diffusivity of lithium and magnesium in the aluminium lattice [11] and the greater tendency for lithium- and magnesium-rich oxide films at the bond interface to ball-up and become discontinuous [14].

In assessing the quality of a bonded joint in thin sheet, comparison is usually made with the shear strength of the base metal, which is calculated assuming a shear/longitudinal tensile strength ratio of 0.6 reported for many aluminium alloys [22]. Thus taking the longitudinal tensile strength (σ_L) obtained in the present tests for the base-metal 4 mm thick sheet in the TC + STA condition (σ_L = 398 MPa, Table IV) the

TABLE IV Longitudinal tensile properties of 8090 alloy sheet

Thickness (mm)	Heat treatment*	Tensile properties			
		0.2 TS (MPa)	TS (MPa)	*E* (GPa)	Elongation (%)
2.5	STA	347	456	76.6	5
	TC + STA	311	429	76.9	5.6
4	STA	298	428	82	14.6
	TC† + SHT	103	265	81	29.7
	TC† + STA	270	398	80	13.7

*TC = 1 h at 560° C.
STA = 20 min 530° C, water quench, 5 h 185° C, air cooled.
†TC = 4 h at 560° C.

TABLE V Shear strengths of 4 mm thick 8090 alloy sheet*

Overlap *l* (mm)	Shear stress, τ (MPa)	Failure load normalized to 11 mm width (kN)	Tensile failure stress (MPa)
2	199	4.5	–
2	203	4.5	–
2.1	202	4.8	–
2.1	209	4.9	–
3	166	5.4	–
3.1	160	5.4	–
3.9	> 131	5.6	249
5.3	> 108	6.2	277

*Type 2 test piece after re-heat treatment to STA condition.

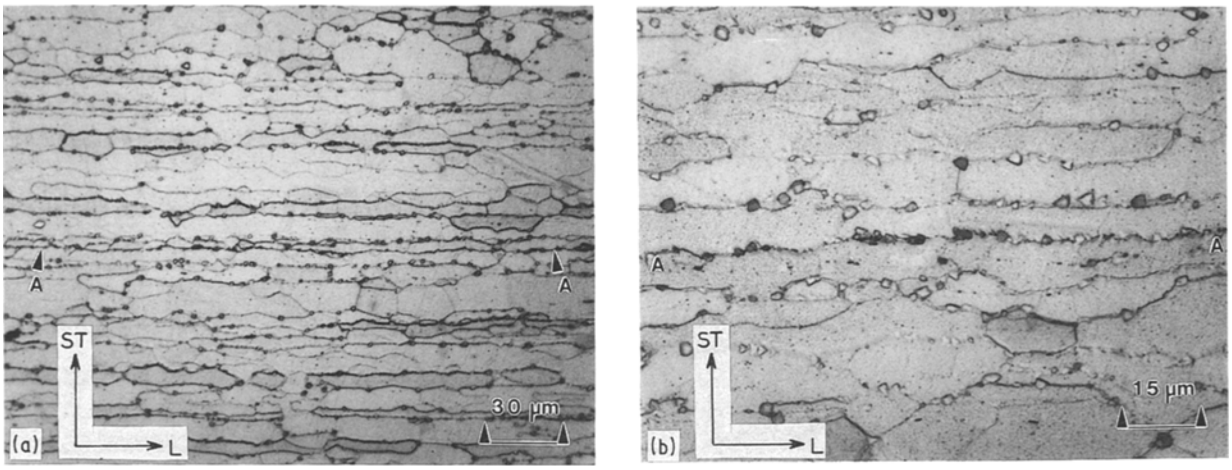


Figure 4 Section through DB joint in unrecrystallized 2.5 mm thick sheet. Surfaces 1200 grit polished. Bond interface A–A.

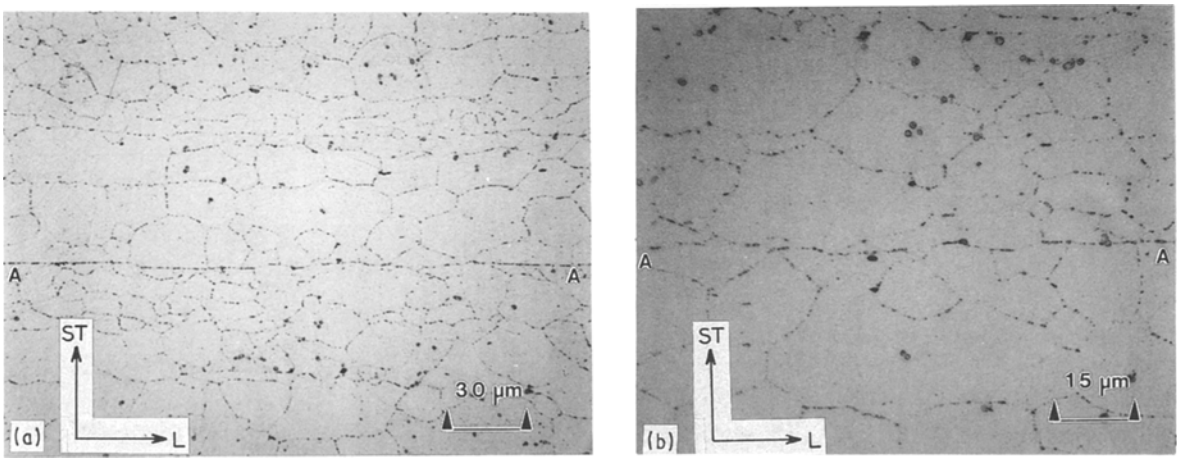


Figure 5 Section through DB joint in partially recrystallized 4 mm thick sheet. Surfaces 1 μm diamond polished. Bond interface A–A.

predicted shear strength is

$$\tau = 0.6\sigma_L = 239\,\text{MPa} \quad (1)$$

This value is much greater than the maximum measured value of 209 MPa (Table V). However, the fracture plane (L–T) in the shear test is characteristic of that obtained in a short transverse (ST) tensile test piece and suggests the tensile strength in this direction (σ_{ST}) should be substituted for σ_L in Equation 1. Although σ_{ST} cannot be obtained for thin sheet, for Al–Li alloy 8090 and 2090 plate in the STA condition [23, 24]

$$\sigma_{ST}/\sigma_L = 0.88 \quad (2)$$

Combining Equations 1 and 2 gives $\tau = 210\,\text{MPa}$, which agrees well with the measured shear strength of the base metal.

A feature of the fractures of the base metal and of the diffusion-bonded joints was the predominance of intergranular fracture. Because of the planar grain-boundary interface produced in the diffusion-bonded joints, these joints exhibited very smooth intergranular shear fracture surfaces compared with the intergranular shear fractures in the base metal. Intergranular fracture is common in the commercial Al–Li alloys 8090 and 2090 [23, 25, 26] which often have well-developed pancake-shaped grains with planar

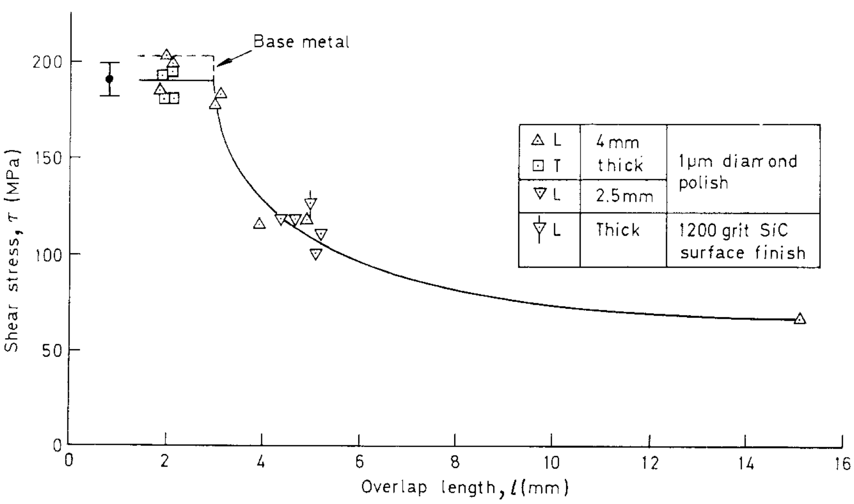
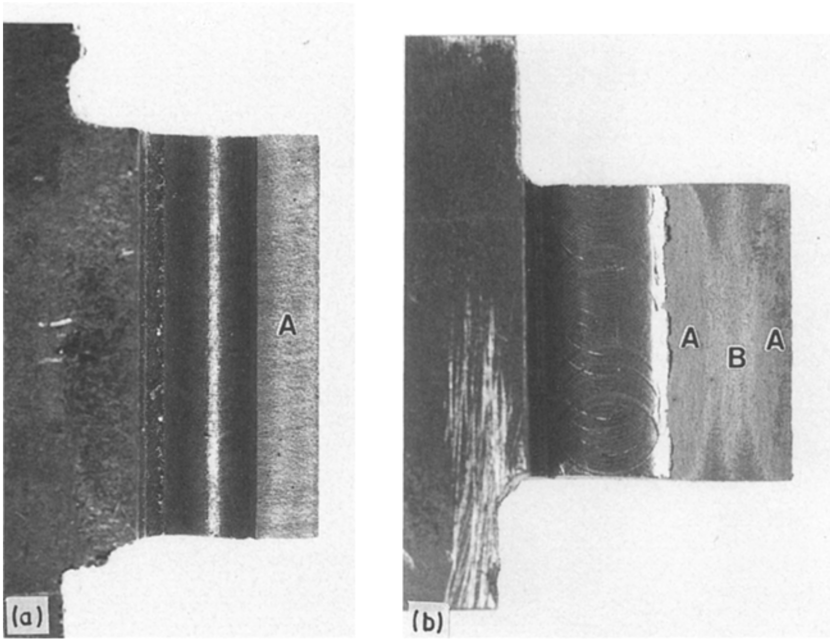


Figure 6 Shear strength plotted against overlap length for 8090 alloy DB sheet in STA condition.



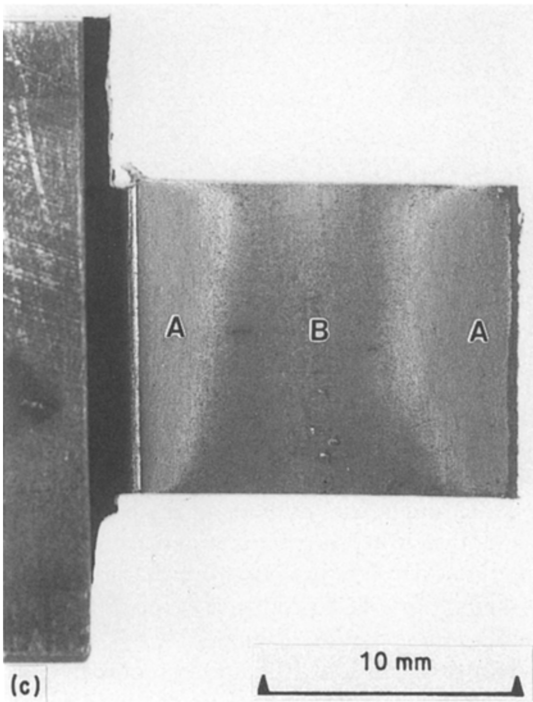


Figure 7 Shear fractures of DB joints in STA condition. Overlap length l (mm): (a) 2.0, (b) 4.7, (c) 15.1. Fracture Zone 1 at A, Zone 2 at B.

grain boundaries in the rolling plane perpendicular to the ST direction. This can lead to low tensile ductility when tested in the ST direction [23–25]. In fracture toughness [25, 27] and fatigue crack growth [24] tests in the L–T and T–L orientations delamination in the rolling plane is beneficial but in fractures perpendicular to the ST direction the lack of crack branching leads to lower toughness and higher crack growth rates. The slightly lower (by 12 MPa) mean plateau shear stress for the diffusion-bonded joint in the present tests is therefore consistent with a reduced resistance to shear crack growth in the planar interface due to reduced crack branching. In all other respects, e.g. the plastic deformation associated with shear fracture and the shear fracture modes observed (see Part 2, [16]) the diffusion-bonded joint behaviour was identical to that of the base metal.

Planar grain-boundary interfaces have been obtained in solid state diffusion-bonded joints in clad

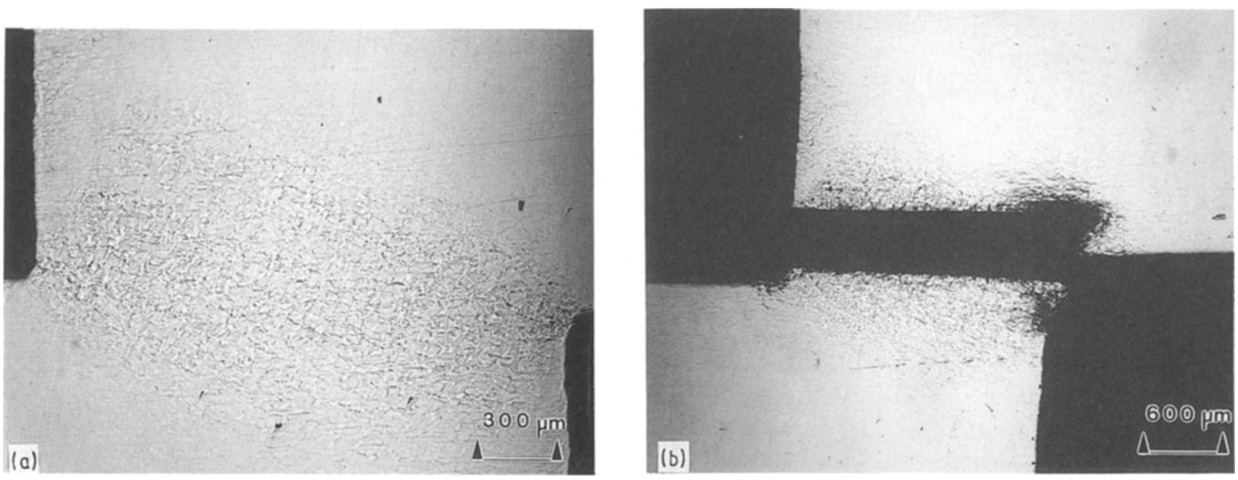


Figure 8 Surface deformation on polished edge of 4 mm thick DB sheet test piece in STA condition with l = 2 mm. Slot combination Type 2/3. (a) Before fracture, (b) after fracture at τ = 202 MPa.

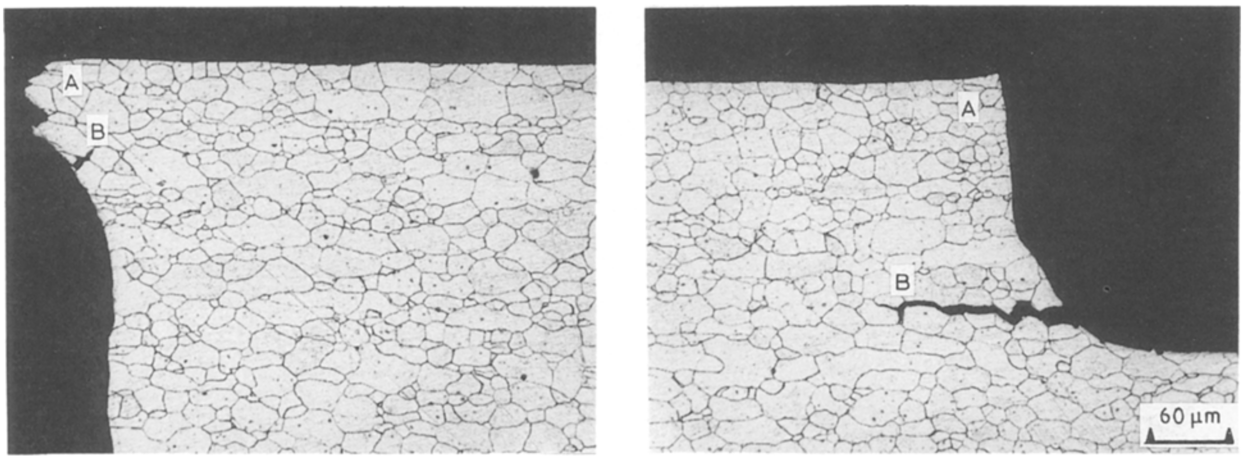


Figure 9 Normal section through bond fracture. Slot combination Type 2/3. Intergranular cracks at base of slots at B, bond fracture plane A–A.

7010 and 7475 alloys [3, 8, 28] but were not observed when a soft interlayer [7] or a transient liquid phase [7, 17] was used. Planar interfaces may be caused by the inherent resistant to grain-boundary migration in the base alloy or by pinning of the grain boundaries by oxide particles derived from the original surfaces [4, 28].

The measured shear strength might be expected to be dependent on the type of notch (Fig. 2) as well as on the degree of bending of the test piece. However, for a given l value there was no significant difference between notched and unnotched test pieces (compare l = 5.1 mm, Table II, and l = 4.9 mm, Table III) and provided the deviation h of the bottom of the notch from the bond plane was small compared with the extent of plastic deformation either side of the bond plane, there appeared to be no effect of notch type on shear strength. Consequently, shear fracture initiated equally well and sometimes simultaneously in the base metal and in the bond interface, but invariably continued in the bond interface even when the slot combination was Type 2/3 (Figs 8 and 9).

In large overlaps the notches caused premature tensile fracture, especially with Type 3 notches; similar effects have been reported for tests on diffusion-bonded joints in 7475 aluminium alloy [6, 7]. However, data obtained with large overlap test pieces are of doubtful value, because the higher peel stresses reduce the measured shear stress and increase the scatter.

5. Conclusions

1. Diffusion-bonded joints can be produced between Al–Li 8090 alloy sheet under 1.5 MPa pressure at 560° C in a vacuum.

2. The curve of shear stress against overlap length exhibited a plateau when $l < 3$ mm; the mean shear strength values in the plateau region for diffusion-bonded joints and for base metal sheet were 191 ± 8 MPa and 203 ± 4 MPa, respectively.

3. Valid shear strengths could only be obtained in the plateau region. For $l > 3$ mm, increased peel stresses and deformation of the test piece led to lower measured shear strengths.

4. A planar grain boundary was produced at the bond interface. The lower resistance to intergranular fracture in this interface led to a slightly lower mean plateau shear strength for the diffusion-bonded joint compared with the base metal sheet.

5. The plateau shear strength values for the bonded joints are greater than previously reported values for Al–Li alloy joints made by solid state or liquid-phase

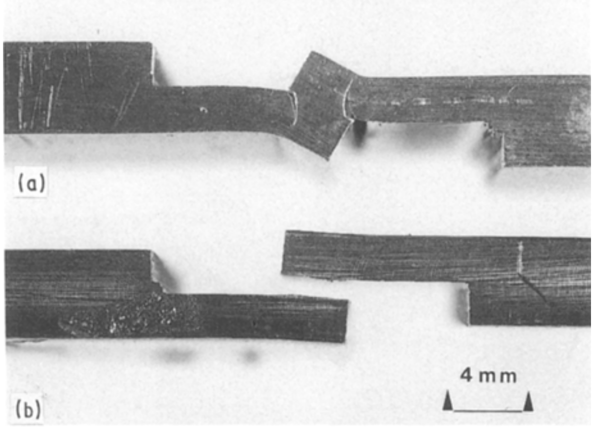


Figure 10 Failure of base metal shear test piece. Slot combination 1/2, (a) in TC + SHT condition, (b) in TC + STA condition.

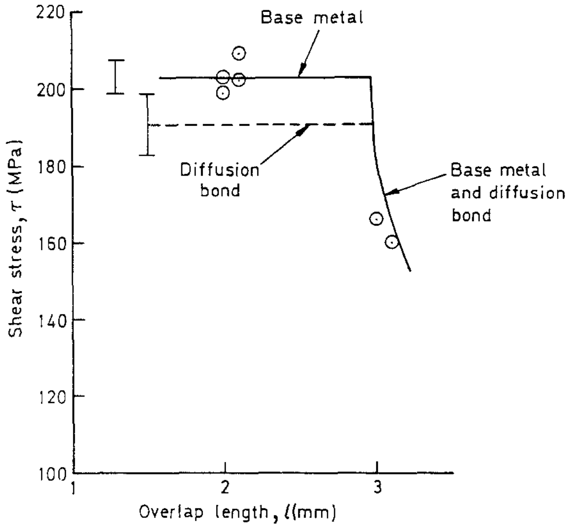


Figure 11 Shear strength plotted against overlap length for 8090 alloy base metal (⊙) TC + STA condition.

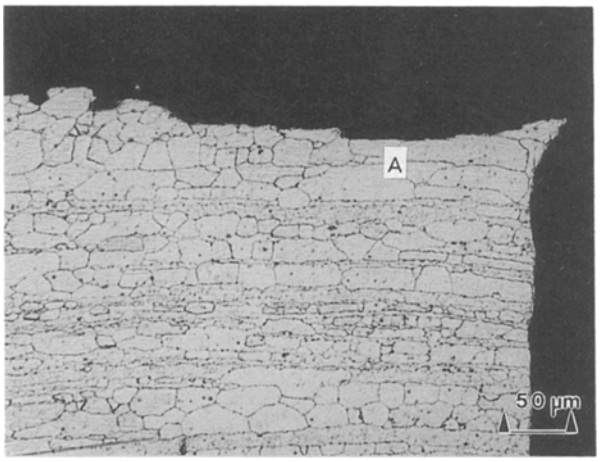


Figure 12 Normal section through shear fracture of base metal test piece. l = 2 mm, τ = 199 MPa.

diffusion bonding and are about a factor of 7 greater than the shear strength of adhesive-bonded Al–Li alloy joints.

Acknowledgements
The authors thank A. J. Shakesheff and D. S. McDarmaid for many helpful discussions. This paper is published with permission of the Controller, HMSO, holder of Crown Copyright.

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Received 14 September
and accepted 1 December 1989