JOURNAL OF MATERIALS SCIENCE 20 (1985) 1009–1014

Diffusion bonding and testing of Al-alloy lap shear test pieces

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A quantitative measure of the effect of processing variables on the shear strength of solid state diffusion bonds is often difficult to obtain because of the scatter in test data. This may be reduced by improving the bonding and testing techniques. Two jigs for bonding and testing small Al-alloy lap shear test pieces are described. These jigs enabled the precise measurement of shear stress–strain curves for lap joints and led to reproducible shear strength values. Results obtained for diffusion bonded lap joints between clad Al–Zn–Mg (7010) alloy are described.

1. Introduction

Solid state diffusion bonding is a vital part of the superplastic forming/diffusion bonding process for titanium airframe structures [1]. Substantial reductions in weight and manufacturing costs can be achieved with these structures compared with a conventional riveted titanium structure [1, 2]. Aluminium alloy sheet can also be made superplastic [3–5] and cost savings might be obtained for aluminium alloy structures if satisfactory bonds could be made.

Although the bond strength depends on the usual processing variables i.e. temperature, pressure, bonding time and interface deformation [6], the oxide film present on Al-alloys is a major obstacle to the formation of high quality bonds [7–9]. Consequently the bond strength of Al-alloys may exhibit a greater dependence on surface finish and on interface deformation than other alloy systems. Unfortunately scatter in the measured bond strength often precludes a precise quantitative assessment of the effect of the above variables [6, 8].

A significant reduction in the scatter might be obtained by improvements in the bonding and testing techniques [10–12]. Recommended lap shear test pieces [12, 13] tend to be large to minimize peel stresses or involve precision machining [13, 14] which makes them expensive. For preliminary research on solid state diffusion bonds two jigs have been designed for bonding and testing small lap shear test pieces. Good repeatability has been obtained for bonds between Al-alloys. The bonding and testing techniques are described in this paper and some shear strength data are presented which illustrate the effect of surface finish.

2. Lap shear test piece

The dimensions of one half of the test piece before bonding are shown in Fig. 1. The specimen length could be adjusted to give different overlap widths. To ensure shear fracture occurs in the bond interface, with high strength bonds the overlap should be $< 2t$ where $t =$ sheet thickness; this may cause problems for $t < 3$ mm. After bonding, a section (A in Fig. 2) was cut from the test piece to enable the as-bonded interface to be examined; after heat treatment the bond interface was examined in a similar cut-out, B in Fig. 2, leaving the lap shear test piece ready for testing.

3. Diffusion bonding technique

During bonding it is essential that the test piece halves are correctly aligned. It is also desirable that the deformation during bonding be measured as well as the pressure and temperature. This was achieved using the bonding jig shown in Fig. 3. Clamp A held one test piece half to the base of the jig and clamp B held the other half to a sliding

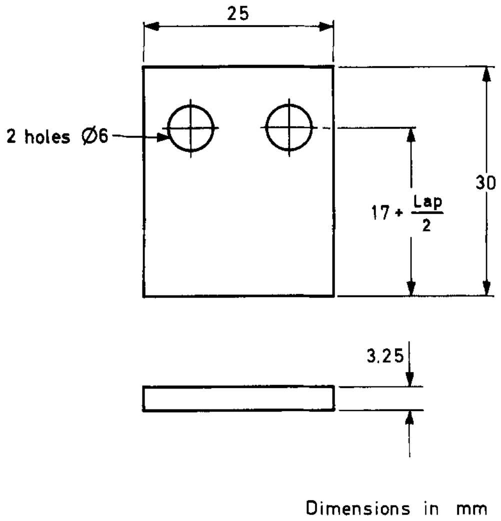

Figure 1 Lap shear test piece half prior to diffusion bonding.

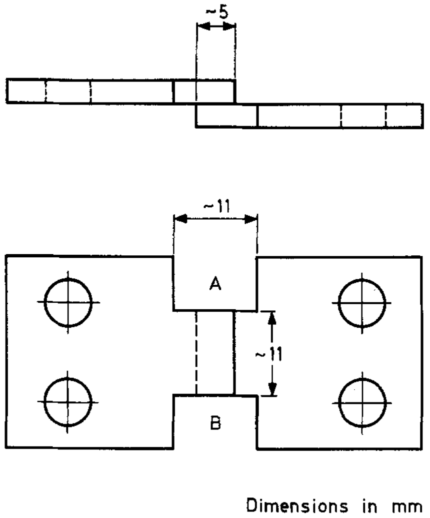

Figure 2 Lap shear test piece.

plunger which was aligned vertically by a fixed top plate and horizontally by a channel. After correcting for the thermal expansion of the jig, the deformation across the bond could be measured continuously by monitoring the height of the plunger and the pressure on the bond by monitoring the load on the plunger.

The small jig size was convenient for bonding under vacuum in a simple sealed tube or for bonding in argon in a tube furnace as shown in Fig. 4. It was sometimes necessary to avoid contact between the two test piece halves until the bonding temperature was reached; this was possible by placing a soft aluminium spacer below the plunger (at B in Fig. 3 and as shown in Fig. 4).

4. Lap shear testing technique

In lap shear tests it is difficult to avoid bending and peel stresses [9–12] and these stresses can lead to variable and low strength values with small test pieces. The jig shown in Fig. 5 was designed to minimize bending and ensure continuous monitoring of the shear stress and strain.

It consists of a fixed plate A with a circular post B which composes the vertical inner sliding section for a rigid plunger C. One end of the test piece is attached to C by clamp D. The other end of the test piece is attached by clamp E to a horizontally sliding frame F. The test piece is first clamped at D and the frame F moved to engage the other end of the test piece. The plunger C

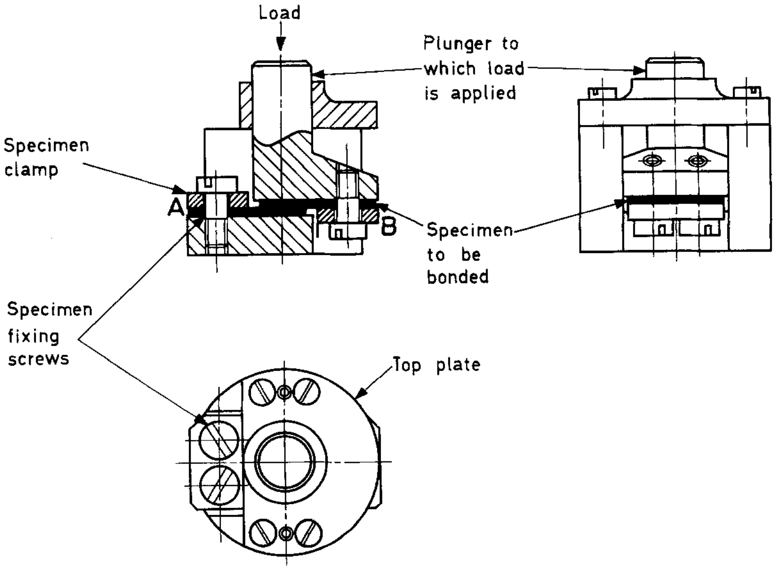

Figure 3 Diffusion-bonding jig.

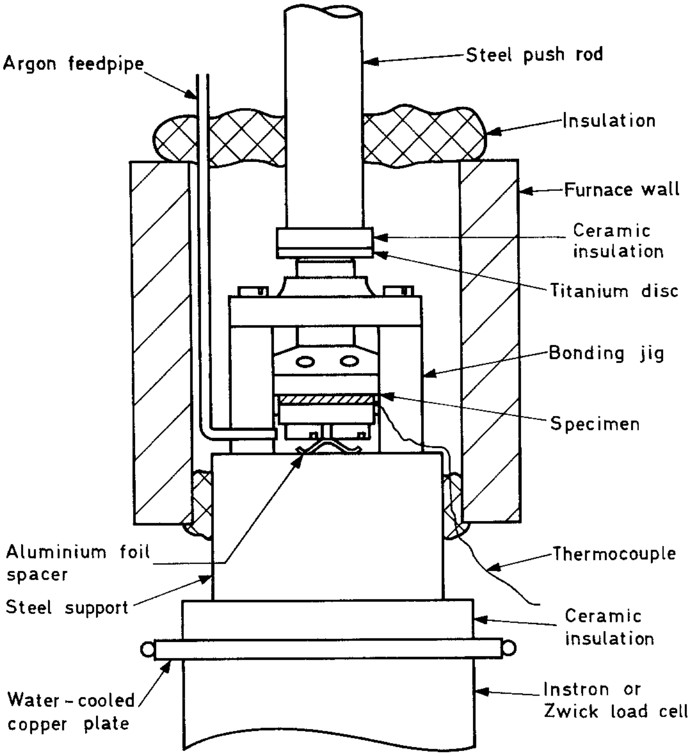

Figure 4 Diffusion-bonding apparatus.

must be raised to locate the test piece at clamp E; a correction must be made to the applied load to take account of the weight of the plunger. The sliding frame is locked into position and the whole assembly provides a rigid testing rig.

5. Deformation and fracture of lap shear test pieces

The bonding and testing techniques described above enabled the precise measurement of compressive load against strain curves up to the onset

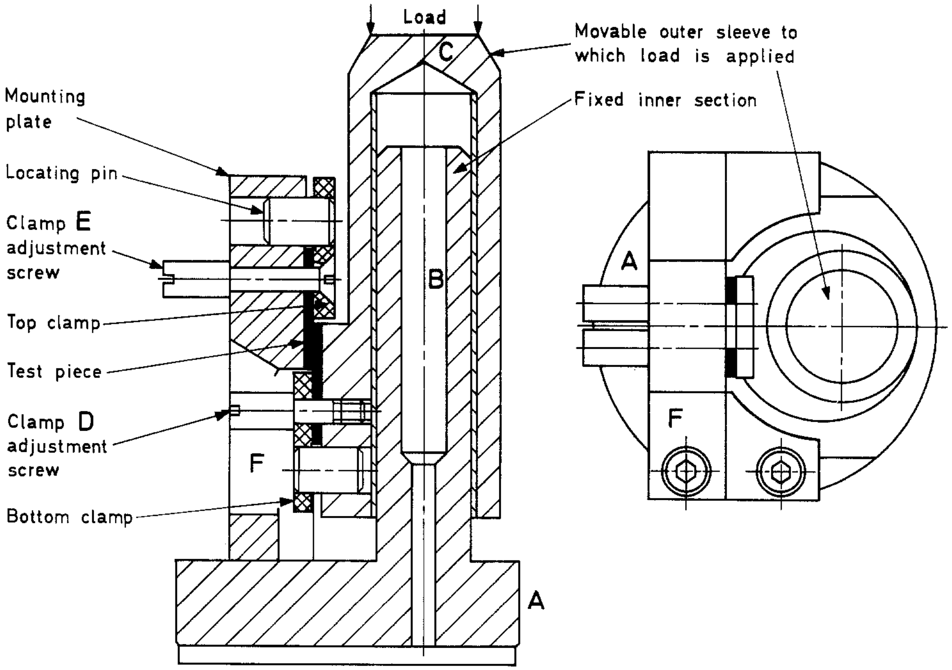

Figure 5 Lap shear test jig.

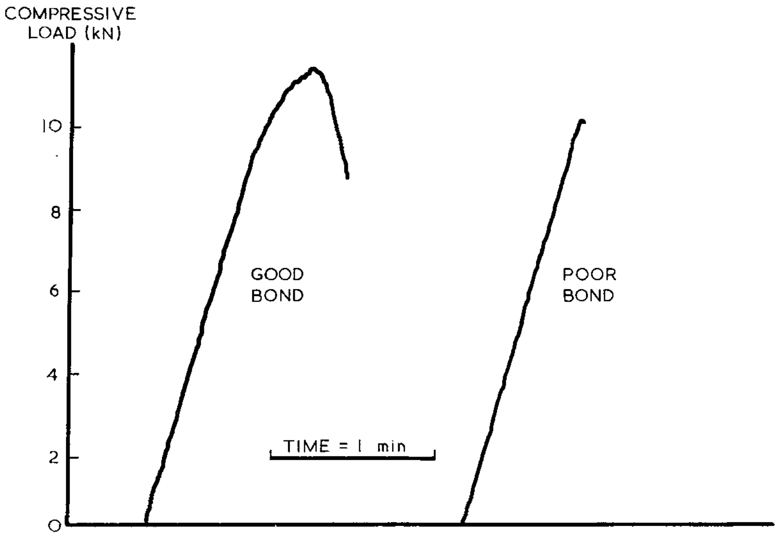

Figure 6 Compressive load against time for diffusion-bonded clad 7010 alloy lap shear test pieces.

of fracture and led to reproducible shear strength values for joints between silver ion-plated clad Al–Zn–Mg (7010) alloy sheet; the bonding conditions were 130 to 150 MPa pressure, 280° C temperature and 10% overall deformation. Typical shear strength data obtained were

1 μm polished sheet surface	171 ± 7.6 MPa (coefficient of variation, CV = 4.5%)
as-clad sheet surface	140 ± 4.5 MPa (CV = 3.2%)
lapped sheet surface	119 ± 6.2 MPa (CV = 5.2%)

It was possible to discriminate between good and poor bonds by the shape of the load against time curves as shown for bonded joints in Al–Zn–Mg alloy in Fig. 6. Plastic shear prior to fracture occurred in good bonds but was absent in poor bonds, although a high shear strength was often obtained in the latter. A rather similar result has been obtained for diffusion bonded butt joints in titanium alloys [15]; residual porosity in the bond interface had little effect on the tensile strength, but caused bond-line fracture with reduced reduction of area. The low ductility of "poor" Al-alloy bonds appeared to be associated with residual porosity or contaminated bond interfaces.

The effect of surface finish, R_z*, on bond shear strength is shown in Fig. 7. The range of surface finish measured in two orthogonal directions is shown in Table I. Unidirectional grinding produced significantly higher shear strength when the grinding directions were parallel in the two bonded test piece halves (P in Fig. 7) than when the grinding directions were normal (X in Fig. 7). These differences are caused by the difficulty in achieving surface contact at the bottom of surface grooves when the scratch directions are normal to each other; this leads to an increase in interface porosity.

Lapping improved the surface finish but did not produce a significant increase in shear strength compared with ground surfaces, but for as-clad sheet or 1 μm diamond polished surfaces with $R_z < 1\,\mu$m substantial increases in bond shear strength were obtained, as shown in Fig. 7. The higher diffusion bond strengths were much stronger than adhesive bonds and comparable with some Al-alloy shear strengths (Table II). The effect of surface finish differed from that found by Ohasi

TABLE I Effect of surface condition on R_z values

Surface condition	R_z value (μm)	
	Longitudinal	Transverse
1 μm Polished	0.37	0.26
As-clad	0.92	0.91
Lapped	1.07	1.36
Chemically polished	1.30	2.11
600 Grit Ground:		
Unidirectional	1.78	2.59
Circular	1.46	1.50

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*An R_z value compares the 5 highest peaks with the 5 lowest troughs on a surface and is defined in [16]. When assessing titanium surfaces for solid state diffusion bonding R_z values were found to correlate better with the surface finish than R_a values [15]. R_z values are generally 4 to 7 times the corresponding R_a value.

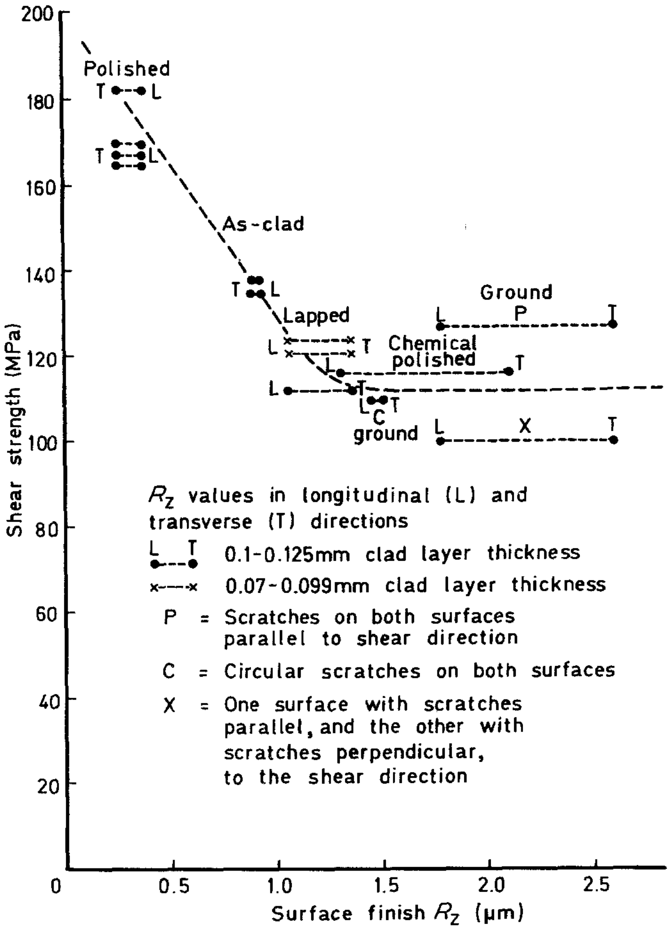

Figure 7 Shear strength against surface finish (R_Z) for diffusion-bonded clad 7010 alloy lap shear test pieces.

and Hashimoto [17] for commercial purity aluminium in which the bond strength increased with an increase in surface roughness. The different effect of surface roughness was probably caused by the bond strength being limited by interface contact area only in the present experiments on silver coated oxide free surfaces, whereas in the experiments of Ohashi and Hashimoto the bond strength was also dependent on the generation of oxide free surfaces. Thus in their experiments this would be favoured by increased roughness which would increase the local deformation of the asperities. In solid state diffusion bonding it may therefore be misleading to generalize and in practice specific bonding data may be required for a given combination of alloy system and bonding technique.

TABLE II Comparison of strengths of aluminium alloys, adhesive bond and 7010 Al-alloy diffusion bond

	Alloy	Condition or temper	Tensile strength (MPa)		Shear strength (MPa)
			Ultimate	Yield	
Parent metal properties [18]	1060	O	69	28	48
		H18	131	124	76
	5254	O	241	117	152
		H38	331	269	197
	6066	O	152	83	97
		T6	393	359	234
	7010	T7651	528	455	320
Adhesive-bonded joint [19]	L73	–	–	–	~ 40
Diffusion-bonded joint	7010	0	–	–	150–180

6. Conclusions

Improved bonding and testing techniques have reduced the scatter in shear strength data for small diffusion-bonded lap shear test pieces. This enabled the precise measurement of shear stress–strain curves for lap joints and led to reproducible shear strength values.

Acknowledgements

The authors wish to thank D. Dunford and A. Lurshay for contributing to the research programme and for providing Figs. 6 and 7. This article is printed by permission of the Controller, HMSO London.

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Received 27 March
and accepted 10 May 1984