FATIGUE OF WELDED AND ADHESIVELY BONDED ALUMINIUM ALLOYS FOR USE IN AUTOMOTIVE APPLICATIONS

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The present study addresses the monotonic fracture and fatigue behaviour of a wide range of joining methods for aluminium alloys. It includes an assessment of resistance (spot) welding, metal inert gas (MIG) welding, laser welding and adhesive bonding for 6000 series (Al-Mg-Si) aluminium alloys tested at room temperature.

The influence of overlap length in the adhesively bonded joints is studied and the additional effect of an adhesive fillet is considered. A comparison of static and fatigue properties for these different types of joining techniques is discussed.

INTRODUCTION

The increased interest in aluminium alloys and aluminium joining technology in the automotive industry over the past few years has been driven by the need for an improved fuel economy, reduced air pollution and greater safety levels. Aluminium is considered to be the best alternative to steel to provide lighter and therefore more fuel efficient cars. Although aluminium, compared to steel is, per given weight, about four times as expensive, savings due to using lightweight aluminium can be achieved on suspensions, brakes and steering wheels. Aluminium sheet unibody, extrusions and cast component spaceframes are currently under extensive study to develop an aluminium alloy car body and chassis at a reasonable price and with acceptable durability.

The use of aluminium for automotive structures has raised questions regarding the joining techniques to be used for the spaceframe technology. Necessary joining methods that provide adequate static and dynamic structural integrity as well as robustness against a crash impact are key to the application of aluminium in the auto body structure.

The construction and assembly of the modern car involves many different joining methods. A wide variety of bonding techniques are applied, each offering special attributes, e.g. shielded arc welding, spot welding etc.

Steel cars are mostly built using spot welding technology. It is widely accepted that the fatigue performance of spot welded aluminium is considerably

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lower than that of spot welded steel. Therefore there are some concerns about the use of spot welding for aluminium automotive structures, although Honda developed a new spot welding system which was then used as the principal joining technology for production of the Honda NSX car (1). The percentage of aluminium in the NSX has been increased to 31.3% in order to achieve a weight reduction of approx. 200 kg. Audi on the other hand adopted for their Audi Space Frame (ASF) continuous shielded arc welding for bonding the aluminium extrusions to the cast aluminium nodes as a major joining technique.

Using adhesives instead of traditional joining methods gives the opportunity for a wider range of materials to be used; a more uniform stress distribution can be obtained; no damage is caused to metal panels; visible spot welds can be avoided; and heat affected zones and residual stresses caused by welding technology may be eliminated. Epoxies show the most promise as adhesives since they are suitable for curing during the paint-bake cycle when the whole structure is assembled. In an automotive plant such a process represents the most convenient and cost effective way of assembly. Although adhesives are widely used in automotive industry they are not presently used in spaceframe bonding. Further research is needed to allow a major breakthrough of such a potentially very attractive joining technique.

EXPERIMENTAL

Materials and specimen preparation

The materials used for fatigue tests of adhesively bonded joints and spot, MIG and laser welded joints were Al-Mg-Si alloy (6000 series aluminium alloy) extruded sheets, supplied by Rover Group U.K. The adhesive used was a formulated epoxy adhesive of 21-29% Bisphenol-A and 11-19% Bisphenol-F containing fillers (XW 1185), supplied by Ciba-Geigy.

The single lap joint was chosen in the present work for the evaluation of adhesive joint performance as being representative of automotive applications. The members of adhesively bonded specimens were machined from the extruded plates with dimensions 20 x 2 x 100 mm^3 and welded joints from welded plates with dimensions 20 x 2 x 180 mm^3. The specimen geometries of the bonded joints employed in current work can be seen in figure 1.

Adhesively bonded specimens: The surface preparation for adhesive bonding involved sandblasting followed by solvent wipe (paper towel soaked in methyl ethyl ketone), additional rinsing in methyl ethyl ketone and degreasing in the same solution for 1 hour at room temperature and finally hot air drying for 20 minutes.

Joints were prepared with a uniform adhesive layer thickness, and with and without adhesive fillets. Although the assumption that, in real automotive structures, an adhesive fillet will not be present is unrealistic, it provides standard condition what can be modelled easily. Two overlap lengths, 20 mm and 30 mm, and two bondline thicknesses, 0.32 mm and 0.19 mm, were investigated as being representative of commercial use. The single lap joint was prehardened according to manufacturer's recommendations at a temperature of 145°C for a period of 15 minutes and final curing was at a temperature of 160°C for 30 minutes.

Laser, MIG and spot welded specimens: 2 mm thick aluminium sheets were welded with an overlap length of 20 mm. In order to reduce the variation in the results, specimens with obvious welding defects were removed.

The laser welded specimens were prepared using a 5kW CO_2 laser with transverse speed of 3 m/min and He gas shielding. The weld was positioned in the middle of the overlap with a thickness of 2 mm. For the MIG welded specimens an average current of 76 A and average voltage of 17 V were required using sifbronze NG21 wire with a transverse speed of 0.75 m/min. The welding was carried out on one side of the overlap only to give a weld thickness of 4mm. Both laser and MIG welding was performed at TWI in Cambridge. Resistance spot welded specimens were supplied by Rover Group with the weld nugget positioned in the middle of the overlap with a diameter of 6 mm.

Monotonic and fatigue tests

The monotonic tests were carried out on a screwdriven servoelectric Zwick 1484 computer operated universal testing machine of 200 kN load cell capacity. The specimens were preloaded to 100N and then a constant displacement rate of 0.1 mm/min was applied.

Constant load amplitude fatigue testing was carried out on a Dartec computer controlled servohydraulic testing machine with 50 kN load cell using a 5 kN subrange. A sinusoidal loading waveform was employed at a frequency of 10 Hz and a stress ratio of R=0. All tests were performed at room temperature. The single lap joint was placed symmetrically in the grips of the testing machine with each grip 50 mm from the nearest edge of the overlap. The grips allow the position of the specimen to be set so the longitudinal force applied by the machine acts in the plane of the bond.

RESULTS AND DISCUSSION

Static tests

Representative stress-stroke curves for different types of joints are shown in fig. 2 and the maximum failure stresses for the adhesive joints are summarised in Table 1.

TABLE 1 - Maximum static failure stresses for adhesively bonded single lap joints with varying bondline thickness, both with and without an adhesive fillet

	3 cm long overlap				2 cm long overlap	
	with fillet		without fillet		without fillet	
bondline thickness	0.19 mm	0.32 mm	0.19 mm	0.32 mm	0.19 mm	0.32 mm
Maximum stress (MPa)	196	196	177	178	118	133

The highest static failure stress is seen for the longer overlap with fillet. Increased overlap and the presence of a fillet both act to increase the static joint performance. It can also be seen that very little difference in maximum stress is observed for the two bondline thicknesses investigated. It must be stressed though that the differences in bondline thicknesses were small enough not to allow the bending moment at the edge of the overlap, caused by the eccentricity of the load path, to vary significantly. Harris and Fay (2) have found for an epoxy (XW 1012) adhesive that the static joint strength is lower with thicker adhesive layers where bondline thicknesses of 0.2, 0.9 and 2 mm thick were used.

The specimens with an adhesive fillet showed an enhanced performance compared to specimens without the fillet. This is due to the fact that the presence of the fillet means that the stress distribution varies significantly from the distribution at the end of the overlap without fillet.

The examination of adhesively bonded fracture surfaces revealed that all the failures have been cohesive in nature where the crack locus is located close to the adhesive/substrate interface, but no interface delamination has been observed. The optical low magnification microscope investigation showed some differences in surface morphology for the two bondline thicknesses (although no effect in static strength was observed) and further research to investigate the micromechanisms of failure is required.

Fig.2 shows that the maximum static failure stress in the substrate for welded joints has been reached in the MIG joint followed by the moderate stress value for the laser weld and the lowest stress value for the spot welded joint. In all welded joints monotonic fracture occurred through the weld. Thus the heat affected zone does not have a significant effect. The difference in static behaviour found in these welded joints is due to the fact that a different bending moment is involved in each case and hence a different type of local stress distribution is applied.

TABLE 2 - The static and fatigue results for different joining methods indicating the failure location

Bond type	Static tests		Fatigue tests	
	maximum stress (MPa)	failure location	fatigue stress at approx. 5.10^5 cycles (MPa)	failure location
Spot welded	74	weld	18	HAZ
MIG welded	166	weld	26	HAZ + weld
Laser welded	101	weld	20	weld
30 mm overlap without fillet, 0.32 mm bondline thickness	178	overlap end	64	overlap end
20 mm overlap without fillet, 0.32 mm bondline thickness	133	overlap end	31	overlap end

Fatigue tests

Fatigue test results of adhesively bonded joints with bondline thicknesses of 0.32 mm and two overlap lengths (20 mm and 30 mm) without an adhesive fillet and welded aluminium joints with 20 mm long overlap are plotted in fig. 3. The results are also summarised in table 2. It may be seen that the majority of results found in MIG, laser and spot welded specimens fall in the same region whereas the fatigue performance of adhesively bonded joints is significantly better than that of welded joints, and the scatter in data of adhesively bonded joints is considerably reduced compared to that of the welded joints. Harris and Fay (2) suggested that initiation in adhesively bonded joints may account for 80% or more of the total fatigue life and also have pointed out, that creep may play a major role in determining fatigue life.

In adhesively bonded joints a uniform stress distribution occurs, as well as there being no heat affected zone which itself may lessen the fatigue resistance (note that failure under fatigue conditions in welded joints may be located within the HAZ, see table 2). Also a larger bonded area in contrast to the established joining methods is often considered to be an advantage. In all cases of welded joints the weld induces local residual stresses and also contains a number of flaws, which are likely to be the main cause of reduction in the fatigue strength compared to that of adhesive joints. Wang et al (3) have investigated the spot-weld-bonded single lap joint and the simply spot welded joint and have found that the adhesive present in the weld-bonded joint not only improves the fatigue strength, but completely changes the failure mode.

During the tests of adhesively bonded joints a Questar QM100 video system was used to monitor the location of initiation of cracks. The test frequency of 10 Hz has been decreased to 1 Hz in order to locate the crack initiation region. It has been confirmed that the cracks starts to initiate at both ends of the overlap verifying the importance of transverse tensile stress, σ_{11}, introduced by the eccentricity of the loading path. The transverse tensile stress dependence on the overlap length and adherend thickness has been calculated using the Hart-Smith analysis as mentioned in article of Kinloch and Osiyemi (4) (using a value of adhesive thickness of 0.32 mm, adherend width of 20 mm and force of 1 kN). The results may be seen from fig. 4 where is evident that the transverse tensile stress plays a more important role for thinner adherend and for shorter overlap lengths. The stress distribution involved in adhesive joints with fillet requires the use of finite element modelling (5) and is the next stage of the investigation.

CONCLUSIONS

This paper deals with monotonic fracture and fatigue properties of single lap geometry joints bonded with MIG, laser, spot welding and adhesive bonding. The main conclusions are as follows:

1. The longer overlap length in adhesively bonded joints gives much better monotonic failure and fatigue behaviour due to reducing the high transverse tensile (peel) stress.
2. In monotonic fracture tests MIG welded specimens showed equivalent performance to adhesive joints with 30 mm overlap, however spot and laser welded specimens possess poorer monotonic properties.
3. The fatigue life of all welded joints falls within the same range whereas adhesively bonded joints exhibited much better properties.

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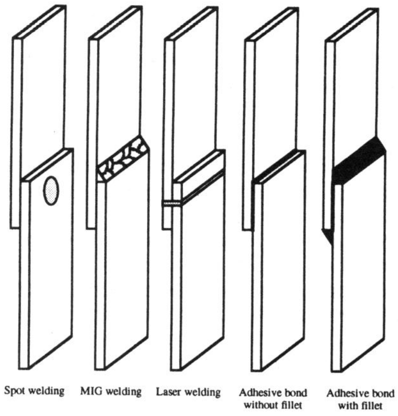

Figure 1 An arrangement of single lap joints employed in current work

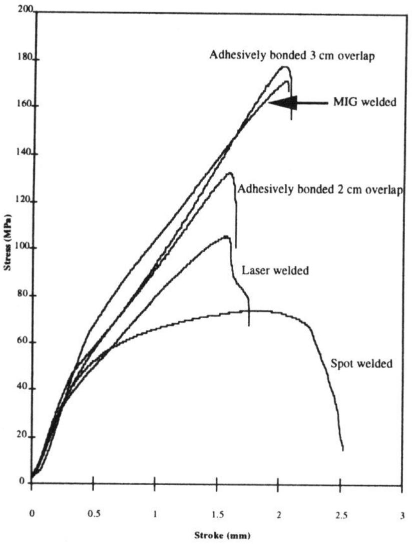

Figure 2 Static stress-stroke curves for different types of joints

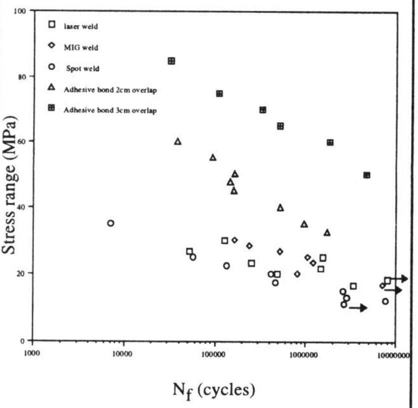

Figure 3 Fatigue life of different types of joints

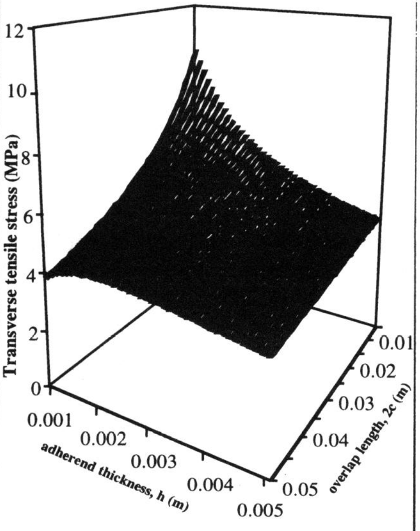

Figure 4 A dependence of transverse tensile stress on overlap length and adherend thickness