MATERIAL AND STRUCTURAL BEHAVIOUR OF MIG BUTT WELDS IN 6000 SERIES ALUMINIUM ALLOY EXTRUSIONS FOR RAIL VEHICLES

W Xu and M F Gittos
TWI Limited, Granta Park, Great Abington, Cambridge, CB1 6AL

ABSTRACT

The welding of 6000 series aluminium alloys can have potentially adverse effects on the material and structural behaviour of the welded joints. In recent accidents involving welded aluminium rail vehicles, some of the longitudinal welds fractured for some metres beyond the zones of severe damage. MIG welding is the main process employed today in the UK and Europe for joining rail vehicle extrusions. This does not mean that the welds will perform as well as the parent material. An extensive mechanical testing programme has been carried out to investigate quasi-static and dynamic material behaviour for the parent material, weld metal and HAZ of MIG welds. The parent material used was 6005A aluminium alloy in the solution treated and artificially aged condition. The filler wires selected were 4043(aluminium-5%silicon) and 5356(aluminium-5%magnesium). Butt welds were produced using conventional procedures in extruded plates and in rail vehicle floor extrusions, from which the test specimens were machined. The testing programme included hardness surveys, tensile, Charpy impact and fracture resistance tests. Structural behaviour of welded rail vehicle floor extrusions has been investigated under quasi-static crush and drop-weight impact loading conditions. These tests were carried out in dynamic servo-hydraulic testing machines and in a 10m drop-weight tower. The present work has concluded that: The aluminium-silicon weld metal was poorer than the weld metal made using aluminium-magnesium filler metal in terms of strength, ductility and fracture resistance; under quasi-static loading, the aluminium-magnesium weld metal outperformed the parent material in terms of the ultimate strength, ductility and fracture toughness; the HAZ was the worst zone in terms of the ability to sustain uniform plastic deformation. By changing from the aluminium-silicon filler to aluminium-magnesium filler, the weld metal strength was greatly improved. Although there might be some scope for improving weld metal strength by consumable development, it is virtually impossible to eliminate the HAZ in conventional MIG fusion welding processes. A programme of work is currently undertaken to explore other options for improvement of joint strength, including redesign of the joint geometry, the use of friction stir welding and of hybrid laser-arc welding.

1 INTRODUCTION

Extrusions of medium strength 6000 series aluminium alloys have been used increasingly in the construction of lightweight transportation vehicles. For the manufacturing of rail vehicle carbodies, modules of the floor, roof and bodyside are produced by welding together longitudinal aluminium alloy extrusions, which are typically about twenty-metres in length. Each weld is of paramount importance to the structural integrity of the vehicle.

The welding of heat treatable 6000 series aluminium alloys can have potentially adverse effects on the material and joint behaviour because of metallurgical changes introduced into the weld zone. Although welded joints designed to conventional codes have performed satisfactorily under the normal operational loads, it is less certain how welded joints will behave under extreme loading conditions. In recent accidents involving welded aluminium rail vehicles, some of the longitudinal welds fractured for some metres beyond the zones of severe damage (Cullen [1]). There is a lack of knowledge for the design of welded joints for high rate loading situations.

MIG welding is the main process employed today in the UK and Europe for joining rail vehicle extrusions. Either aluminium-silicon or aluminium-magnesium fillers have been used for the welding of 6000 series aluminium alloys, but this does not mean that the welds will perform as well as the parent material. There is a need to investigate the effects of the use of different filler metals on the structural behaviour of the welds.

Mechanical tests have been conducted to investigate material behaviour for the parent material, weld metal and HAZ of MIG welds made using either aluminium-silicon or aluminium-magnesium fillers. These included hardness surveys, tensile, Charpy impact and fracture resistance tests. Joint behaviour in quasi-static crush and drop-weight impact tests has been investigated by component testing. The objectives of this work were to provide physical evidence of material and structural behaviour of MIG welds in 6000 series aluminium alloy extrusions under quasi-static and impact loading; and to compare material and structural behaviour of MIG welds made using aluminium-silicon and aluminium-magnesium fillers.

2 MATERIALS

The parent material used was 6005A aluminium alloy in the solution treated and artificially aged condition. It is currently widely used for the construction of rail vehicle carbodies. Flat, extruded plates and rail vehicle floor extrusions of this alloy were employed for the test work. The filler wires selected were 4043(aluminium-5%silicon) and 5356(aluminium-5%magnesium), as these have been used in production of rail vehicle body structures in the UK and these are also the candidate welding consumables listed in British Standard BS8118-1:1991 [2] and Eurocode 9 [3].

3 WELD PRODUCTION

Butt welds were produced using conventional procedures with the MIG process using 4043 and 5356 filler wires. Butt welds in the extruded plates were made in two passes and those in the rail vehicle floor extrusions were produced with a single pass procedure. Further details of the welding can be found in Ref.4.

4 SPECIMEN PRODUCTION AND DESCRIPTION

Full thickness rectangular and circular cross section specimens were used in tensile tests. Most of the specimens were extracted in the direction parallel to the extrusion direction, which is the same as the welding direction, but some circular cross section specimens were extracted transverse to the direction of extrusion to check the possible anisotropic material behaviour. All-weld-metal specimens were extracted from the welded extruded plates in the direction parallel to the weld length. The specimen axis coincided, nominally, with the weld centre line. Tensile specimens from the HAZ were taken immediately next to the weld metal.

Charpy specimens of dimensions 5x10x55mm^3 were extracted transverse to the weld length and through-thickness notched.

Fracture mechanics single edge notch bend (SENB) specimens, as per BS 7448-4:1997 [5], were extracted from the welded extruded plates. Specimens of Bx3B, where B is the specimen thickness equal to 5mm, were used. These were extracted transverse to the weld and through-thickness notched either at the weld centre line or with the notch aimed to intercept the fusion boundary at the mid-thickness. The crack depth to specimen width ratio was nominally equal to 0.35.

Specimens for quasi-static crush and drop-weight impact testing were machined from rail vehicle floor extrusions. Specimen designs are described in Ref. 4.

5 TEST PROCEDURES

All fracture resistance tests were carried out in three point bending. The tests at slow rates of increase of the stress intensity factor were performed in accordance with BS 7448-4:1997 [5]. The rate of increase of the stress intensity factor was about 0.55MPam$^{1/2}$/s.

Fracture resistance curves were determined using the multiple specimen test procedure in BS 7448-4:1997 [5]. Fracture toughness was quantified in terms of J, which was estimated using the method described in a draft revision to ASTM 1290 (see also Pisarski and Wignall [6]).

Intermediate rate tests were carried out using a servo-hydraulic testing machine. The nominal load line displacement rate was 450mm/s. The rates of increase of the linear stress intensity factor were between 6,000 and 24,000MPam$^{1/2}$/s. The testing procedures for the intermediate rate tests were those developed by Wiesner [7].

The quasi-static crush tests were carried out using a servo-hydraulic testing machine with a maximum load capacity of 1,800kN. The specimen was subjected to an axial compressive load applied under a slow displacement rate of 6mm/min.

The drop-weight impact tests were performed using a drop-weight testing machine. A total mass of 102kg can be dropped from a maximum height of 9.8m. The testing procedures used for the present tests were similar to those developed previously at TWI (Wiesner and Bell[8]). The displacement of the impacting mass was calculated from the measured load versus time data.

6 TEST RESULTS

Vickers hardness results indicated reductions in the hardness values of the weld metal and the HAZ as compared to the hardness (about 100HV5) of the parent material. The width of the zone of reduced hardness was about 30-40mm for the welds made in this work. The lowest hardness value (about 45HV5) for the Al-Si filler welded joints was in the weld metal. The hardness value (about 60HV5) of the weld metal was similar to that of the HAZ for the Al-Mg filler welded joints.

The average values of tensile properties for the different material zones are listed in Table 1. The lowest 0.2% proof strength, ultimate strength and area reduction were measured in the weld metal made with aluminium-silicon filler. Although the 0.2% proof strength of the weld metal of the aluminium-magnesium filler weld was about 55% of that of the parent material, its ultimate strength was slightly higher than that of the parent material. The elongation of the HAZ at the maximum load is relatively low, only 4 to 5%. Both weld metals elongated a relatively small amount after the maximum load had been reached.

The average Charpy energy of the parent material was about 6J. The lowest Charpy energy, 5J, was measured in the Al-Si filler weld metal. The highest average, 18J, was measured in the weld metal of the weld made with the Al-Mg filler.

The quasi-static and dynamic J R-curves of the parent material and the two weld metals are compared in Fig.1 and Fig.2. Under both quasi-static and dynamic loading conditions, for crack extensions greater than 0.5mm, the highest and the lowest J values were for the aluminium-magnesium filler metal and the aluminium-silicon filler metal, respectively. The slopes of the J R-curves of the weld metal made with aluminium-magnesium filler were steepest under dynamic loading, while the slopes of the J R –curves of the weld metal made with aluminium-silicon filler were considerably flatter.

Some of the rail vehicle floor extrusion specimens after the quasi-static crush tests are shown in Fig.3. The welds did not fail completely by fracture, although severe plastic deformation occurred in the parent material. There were small cracks parallel or transverse to the weld length in the aluminium-silicon weld metal and the HAZ. No cracks were observed in the Al-Mg weld metal and HAZ.

Some of the rail vehicle floor extrusion specimens after the drop-weight impact tests are shown in Fig.4. The welds survived the impact loading. Tearing damage and cracks were observed in the parent material at the corners. Small cracks were observed in the Al-Si weld metal. Note that no cracks were observed in the corresponding specimens tested under quasi-static loading.

Table 1: Average values of tensile properties

Material	$\sigma_{0.2\%}$, MPa	σ_{UTS}, MPa	A %	Ag, %	Z, %
Parent	254.3	278.5	12.4	7.5	33.6
Al-Si WM	105.2	196.3	13.9	12.6	18.6
Al-Si HAZ	180.1	230.0	11.2	5.1	51.3
Al-Mg WM	138.8	283.6	22.8	20.6	37.6
Al-Mg HAZ	176.9	224.2	8.6	3.9	43.0

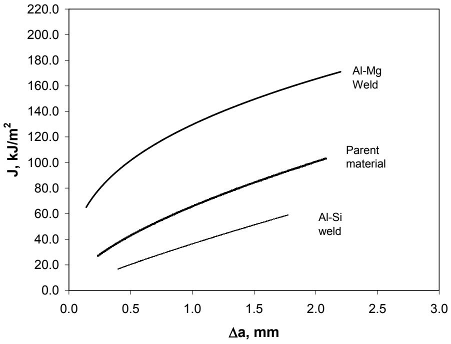

Figure1: Quasi-static J R-curves

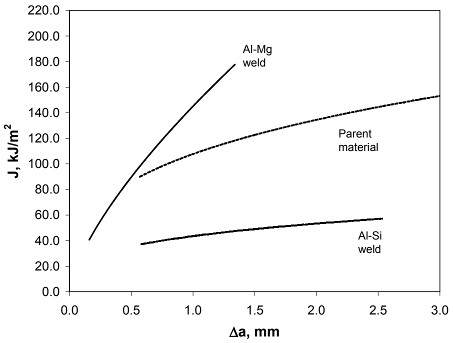

Figure 2: Dynamic J R-curves

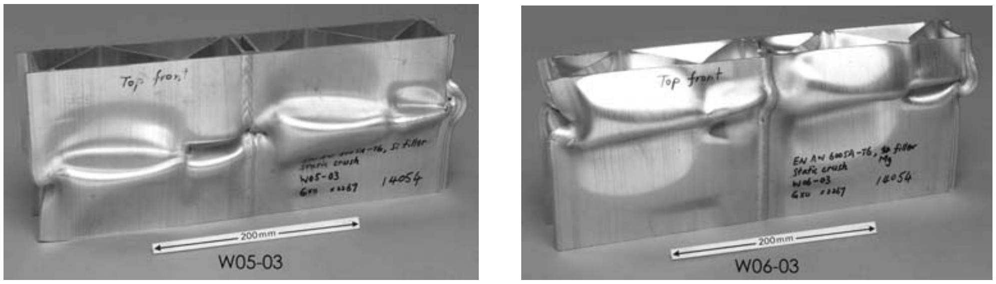

Figure 3: Rail vehicle floor extrusion components after quasi-static crush tests

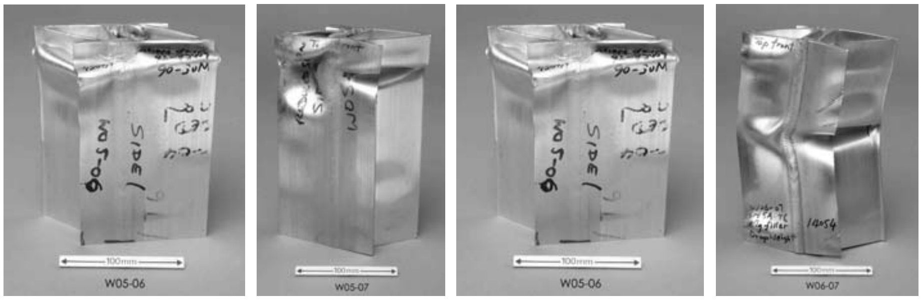

Figure 4: Rail vehicle floor extrusion components after drop-weight impact tests

7 DISCUSSION

It is important to note that the properties of welded joints in 6000 series aluminium alloys are, to some extent, specific to the particular joints tested. For example, different filler metal dilutions, weld heat inputs and heat treatments can all modify the properties of the weld metal and HAZ regions (Scott and Gittos[9]). For the welds made in this work, the tensile test results of the parent material, the weld metal and the HAZ show that the aluminium-silicon weld metal was the weakest zone in the joints made using the aluminium-silicon filler. The HAZ was the weakest zone in the joints made using the aluminium-magnesium filler. The strength of the weakest zone was significantly lower than that of the parent material. By changing from the aluminium-silicon filler to aluminium-magnesium filler, the weld metal strength was greatly improved. Although there might be some scope for improving weld metal strength by consumable development, it is virtually impossible to eliminate the HAZ in conventional MIG fusion welding processes. Other options for improvement are currently being explored. These include redesign of the joint geometry, the use of non-fusion welding, laser and hybrid laser-arc welding (ALJOIN[10]).

The weak zones in the welded joints may or may not affect the joint behaviour significantly, depending in part on the loading modes. Under axial crush or impact loading, complete fractures did not occur in the weld metal and the HAZ. This is probably because the tensile forces perpendicular to the weld in the tests were too low. High tensile forces across the weld, however, can be generated when the lateral restraint on the weld is severe. This has been confirmed by finite element analyses of a complete rail vehicle body structure under head-on collision (Wilson[11]). Structural behaviour of welded aluminium alloy joints subjected to tension or bending is currently under investigation. Initial test results showed that complete fracture occurred in the zone of the lowest strength (Xu and Gittos[12]). As many loading modes co-exist under crash loading conditions, the effects of the weak zones on the performance of the structure should be evaluated against the most damaging loading mode, which is probably tension across the weld.

Strength, ductility and fracture resistance are the main mechanical properties which will have a big influence on performance of structures under static overload and dynamic crash conditions. The use of aluminium-magnesium filler in the welding of aluminium alloy extrusions would be beneficial for these loading conditions. Other properties such as welding process operability, cracking susceptibility, fatigue durability and corrosion resistance are also important for the construction and safe and economic operation of welded aluminium alloy structures. Aluminium-silicon fillers are known to be easier to use and less susceptible to cracking than aluminium-magnesium fillers. Aluminium-silicon fillers may be preferred because of these characteristics for specific applications. However, a full discussion on the selection of filler wires is out of the scope of this paper. Further information can be found elsewhere (e.g. Gittos and Scott[13] and Scott and Gittos[14]).

Based on finite element analyses and the fracture mechanics test results of SENB specimens, it was estimated that strain rates at the tip of the crack were in the order of 1/250 to 1/500 (Xu and Gittos[4]). In rail vehicle crash scenarios, different parts of the vehicle body experience different strain rates, depending on the vehicle design and the crash scenario. Further work is required to determine strain rates in the longitudinal welds in rail vehicle body structures. The significance of the strain rates achieved in the SENB fracture mechanics tests can be assessed when the strain rates in the vehicle are available.

8 CONCLUSIONS

An extensive mechanical testing programme has been carried out on aluminium-silicon and aluminium-magnesium welds in 6005A-T6 extruded components, employing a range of strain rates. The analyses of the test results have led to the following main conclusions:

1. The aluminium-silicon weld metal in the extruded plates was poorer than the weld metal made using aluminium-magnesium filler metal in terms of strength, ductility and fracture resistance.
2. Under quasi-static loading, the aluminium-magnesium weld metal in the extruded plate outperformed the parent material in terms of the ultimate strength, ductility and fracture toughness, but its 0.2% proof strength was lower than the parent material.
3. In terms of the ability to sustain uniform plastic deformation, the HAZ was the worst zone, as indicated by the smallest amount of elongation at the maximum load. This, coupled with the lower strength than the parent material, will cause strain localization in the HAZ.
4. Although the weaker weld metal and the HAZ did not cause complete fractures of the welded rail vehicle floor extrusions under the predominately compressive mode of loading, the effects of the weak zones on the performance of welded structural components should be evaluated against the most damaging loading mode in situations where several loading modes co-exist.

9 ACKNOWLEDGEMENT

The work was funded by Industrial Members of TWI, as part of the Core Research Programme, and by the European Commission, as part of the ALJOIN Project.

10 REFERENCES

1. Cullen W D: ‘The Ladbroke Grove rail inquiry – Part 1’. HSE, 2001.
2. BS 8118-1:1991: ‘Structural use of aluminium – Part 1: Code of practice for design’. British Standards Institution, London, 1991.
3. DD ENV 1999-1-1:2000: ‘Eurocode 9: Design of aluminium structures – Part 1-1: General rules – General rules and rules for buildings’. British Standards Institution, London, 2000.
4. W Xu and M F Gittos: ‘Material and structural behaviour of MIG butt welds in 6005A-T6 aluminium alloy extrusions under quasi-static and impact loading’. TWI Report No. 14054/1/04, February 2004.
5. BS7448: ‘Fracture mechanics toughness tests, Part 4: Method for determination of fracture resistance curves and initiation values for stable crack extension in metallic materials’. British Standards Institution, London, 1997.
6. Pisarski H G and Wignall C M: ‘Fracture toughness estimation for pipe girth welds’. Proceedings of IPC 2002 International Pipeline Conference, 29 sep – 3 Oct 2002, Calgary, Albert, Canada.
7. Wiesner C S: ‘Dynamic J-R curve determination’. Materialprüfung, Vol.34, pp12-16, 1993.
8. Wiesner C S and K Bell: ‘Significance of strain rate effects in defining transition toughness’. TWI Report No. 220402/2/96, December 1996.
9. Scott M H and Gittos M F: “Tensile and Toughness Properties of Arc-Welded 5083 and 6082 Aluminium Alloys”, Welding J. Res. Suppl., September 1983, pp244-252s.
10. ALJOIN – Crashworthiness of joints in aluminium rail vehicle, EU funded project under the Competitive and Sustainable Growth Programme. Project No. GRD2-2001-50065.
11. Wilson M J, Bombardier Transportation UK, private communication, 2004.
12. W Xu and M F Gittos : ‘Mechanical testing and finite element modelling of aluminium alloy welds under hogh strain rate : Initial results’. TWI Report No. 785, December 2003.
13. Gittos M F and Scott M H : ‘Selection of filler metals for arc welding aluminium alloys : 1-General principles and British alloys.’, The Welding Institute Research Bulletin, August 1987, pp.259-263
14. Scott M H and Gittos M F: ‘Selection of filler metals for arc welding aluminium alloys : 2-Alloys of other countries.’, The Welding Institute Research Bulletin, Februnary 1988, pp.57-59.