STATIC AND DYNAMIC PROPERTIES OF JOINTS IN THIN-WALLED ALUMINIUM EXTRUSIONS, WELDED WITH DIFFERENT METHODS

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ABSTRACT

This paper presents mechanical properties of welded joints in thin-walled extruded Al-Mg-Si-alloys, both tensile and fatigue properties are included. Tungsten inert gas (TIG), metal inert gas (MIG), and friction stir (FS) welding are considered. TIG welding gave large heat affected zone widths; 20 mm compared with HAZ widths of 10 mm and 8 mm for MIG- and FS welding respectively. This relationship was also seen in tensile tests where FS specimens exhibited the highest strength and TIG specimens the lowest strength. Post-weld aged materials recovered some strength, an increase of 20 % was found. Comparisons between the experimental data and the draft European standard show that the European standard is conservative for welds in thin-walled material.

Fatigue results of FS welded material are compared with the European Recommendations for Aluminium Alloy Structures Fatigue Design (ERAAS). Two types of fatigue tests were performed, strain controlled testing on small specimens and common stress controlled fatigue testing on larger specimens. FS welded specimens showed very high fatigue performance in both cases.

Keywords: Aluminium, Al-Mg-Si, hardenable, weld, TIG, MIG, friction stir welding, mechanical properties, fatigue

1. INTRODUCTION

Thin walled hollow sectioned components of extruded aluminium alloys can effectively be assembled into high strength, rigid and light structures. The joining of separate beams is often achieved by welding and it is a well-known fact that welded joints in hardenable aluminium alloys suffer from reduced tensile strength as well as reduced fatigue strength. The knowledge of strength and deformation capacity in welded joints in thin-walled extrusions is limited for both static and fatigue loading and further research is needed. Experimental results on large beams with plate thickness of 10 mm or more, and/or laboratory tests on small specimens dominate reports and articles in the open literature. Design rules and standards are mainly based on these experimental results and therefore special thin-wall effects are not well accounted for.

The purpose of the present work is to describe the tensile properties of welded joints in thin-walled extrusions and to study the differences between the three welding processes MIG, TIG and friction stir welding. Fatigue data is given for FS welded specimens and compared to recommendations of today.

2. EXPERIMENTAL

2.1 Material

Extruded hollow-sectioned square beams of a high strength, hardenable Al-Mg-Si aluminium alloy, EN AW-6082 (Al-Si1-Mg-Mn), was used. This alloy contains additions of magnesium and silicon, which in the heat-treated and aged condition precipitate Mg_2Si as a hardening phase. The silicon content in the alloy is above the stoichiometric level. Manganese is added to improve toughness and corrosion resistance. The chemical composition of the alloy is presented in Table 1. The material w heat treated to temper T5 (no separate solution heat treatment after extrusion, then artificially ag Material properties are given in Table 2. The dimension of the beam was 50*50 mm with a wall thi ness of 2.5 mm (Fig. 1).

Table 1 Control analysis of the material, wt-%

Alloy	Value	Mg	Si	Mn	Cr	Cu	Fe	Ti	Zn	Al
6082	Min	0.57	0.91	0.45	…	…	0.21	0.01	…	Bal.
	Max	0.59	0.94	0.46	<0.01	<0.01	0.22	0.02	0.02	Bal.

Table 2 Mechanical properties of parent material

Alloy	Value	Yield strength, MPa	Tensile strength, MPa	Elongation A_{50}, %
6082	Min	285	295	6.8
	Max	291	310	8.9
	Ave	287	302	8.0

2.2 Welding

Metal inert gas and tungsten inert gas welding are the most commonly used processes for weld aluminium. MIG welding employs an aluminium wire as a combined electrode and filler metal i direct current arc. TIG welding uses a non-consumable tungsten electrode; a separate wire adds fil metal. MIG welding is faster than TIG welding and less heat is therefore accumulated during the pro ess. For thin material, TIG is often used since MIG gives difficulties with material thickness below mm. TIG welding is also more stable when welding by hand and is often used when there is a hi demand on weld quality (1,2). The welding was performed at workshops with special competence f aluminium welding. Filler wires used were; 4047 (Al-Si12) (MIG) and 5356 (Al-Mg5) (TIG), the w diameter was 1.2 mm for MIG- and 2.5 mm for TIG welding. The shielding gas was pure argon f MIG- and argon with 30 % helium for TIG welding. The voltage and current were about 20 V and 1 A for both processes. The beams were welded together to T-shaped components (Fig. 1).

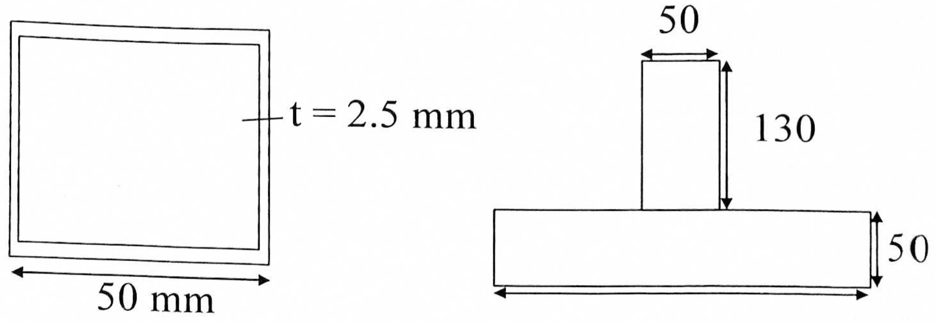

Fig. 1 a) Cross-section of the beam; b) Welded component with vertical and horizontal beams A and B

Friction stir welding [3, 4] uses friction as heating source during welding. The process does not quire filler wires and shielding gas, it is energy efficient, it is easily automated, and it introduces re tively small amounts of heat into the work material. The FS welding process needs a solid back when welding thin material. The process also needs a symmetric joint and, currently, can only be us to produce butt welds. Owing to these limitations it is not possible to weld components in the sa way as with arc-welding processes. Flat pieces, therefore, were cut out from the extruded beam and welded.

2.3 Post-Weld Heat Treatment to Recover Strength

It is possible to recover some of the lost strength by repeating the ageing. The ageing is performed at a lower temperature than the solution heat treatment (170-200°C for Al-Mg-Si-alloys compared with 500°C), and therefore results in less distortion. By only carrying out the ageing procedure, considerable improvement in strength can be achieved, but it also reduces ductility. The material unaffected by welding becomes slightly overaged in this way and a zone that is overaged by the weld heat is further aged by the post-weld ageing procedure. The ageing of the TIG welded components and FS welded material was conducted at 180 °C for 6 and 4 hours respectively. Ageing curves [5] show that the parent metal strength is not affected very much by the over ageing at these temperatures and times.

2.4 Tensile Testing and Hardness Measurements

The tensile testing was performed on a PC-controlled, electro-mechanical test machine (+/- 50 kN). The elongation rate was 0.1 %/s. The tensile specimens were fabricated according to the ASTM standard with a 50 mm parallel section.

Vickers hardness testing with 10 kg weight was used.

2.5 Fatigue Testing

The small specimens for strain controlled testing were 100 mm long and 20 mm wide with a thickness of 2.2 mm. A waist of 25 mm was milled out and then the machined surfaces were polished with diamond paste before testing. The parent material specimens were tested in the extrusion direction. The friction stir welded specimens were tested "as-welded"; no improvement of the surface was introduced. The elongation was measured over a 6 mm parallel gauge section. The extensometer knives were attached on thin brass foil, glued to the specimen. The tests were carried out with fully reversed strain (R_ε equal to -1), in a closed loop servo hydraulic test machine. The strain rate was 0.02 to 0.05 s^{-1}. The tests were run until fracture, or the specimen had survived more than 1.2 million cycles.

The stress controlled testing was run on 5 mm thick specimens, 250 mm long and 70 mm wide. No waist was used. The tests were carried out with a stress ratio (R-value) of +0.5, in a closed loop servo hydraulic test machine.

3. RESULTS

3.1 Tensile Testing

The results for the *parent metal tensile testing* are presented in Table 2. The average yield and tensile strengths are 287 and 302 MPa.

MIG welded specimens fractured in the HAZ with tensile strengths of 213 to 239 MPa. Table 3 contains the results. Average tensile strength and elongation was 218 MPa (72 % of the parent materials strength) and 6.0 % respectively.

All tests of *TIG welded specimens* fractured in the HAZ. The tensile strength ranged from 156 to 176 MPa. The average tensile strength was 170 MPa, 56 % of the parent material strength. The elongation was 7.0 %. The post-weld aged material recovered in strength, the tensile strength was raised by more than 20 % (Table 3), average strength was 207 MPa or 69 % of the parent metals strength. The elongation decreased though, from 7.0 % to 2.2 %.

The FS welded material showed a tensile strength of 219-226 MPa in the as-welded condition, which was considerably higher than the arc-welded material. The elongation was lower, 4.9 %. After ageing for four hours at 180 °C the tensile strength was 257-261 MPa, an increase with 15-20 %. Average tensile strength for the as-welded material was 223 MPa and for the post-weld material 260 MPa, it corresponds to 74 % and 86 % of the parent metals strength.

Table 3 Average mechanical properties of cross welds

Material	Condition	Tensile strength, MPa	Elongation A_{50}, %
MIG	As welded	218	6.0
TIG	As welded	170	7.0
	Post-weld aged	207	2.2
FS	As welded	223	4.9
	Post-weld aged	260	2.2

3.2 Hardness Measurements

Hardness profiles over MIG-, TIG- and FS welded joints are compared in Fig. 2. The extent HAZ is dependent on the heat input. The HAZ was 18-22 mm for TIG welds compared to 9-10 for MIG welds and 8-9 mm for FS welds.

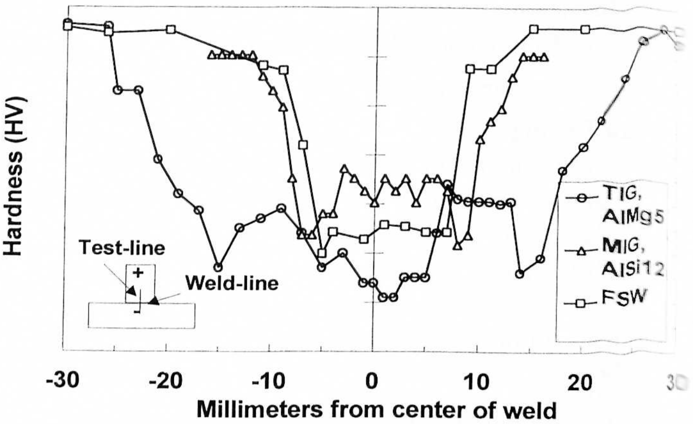

Fig. 2 Hardness profiles across MIG, TIG and FS welds.

Post-weld aged materials recovered strength (hardness) in the HAZ and the soft zone decreased significantly. This change is however not only related to the width of the HAZ but also the depth of the hardness drop. The characteristic HAZ profile changed from one soft zone covering the HAZ width, to two narrow ditches on either side of the weld zone, which is favourable. The h ness of the unaffected metal decreased marginally after the second ageing.

3.3 Fatigue

The strain amplitude vs. life for the FS welded specimens is plotted in Fig. 3. The total strain plitudes as well as the elastic and plastic components are included in the figure. The constants Eq. 1, describing the elastic and plastic parts of the curve, are given in Table 4.

$$\varepsilon_a = \varepsilon_e + \varepsilon_p = \frac{\sigma'_f}{E}(2N_f)^b + \varepsilon'_f\left(2N_f\right)^c \qquad (1)$$

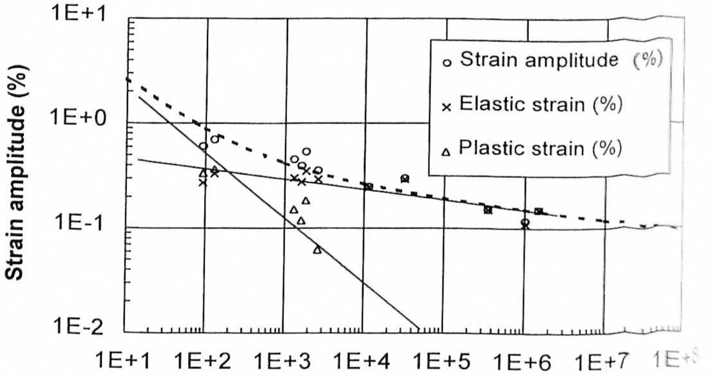

Fig. 3 Strain vs. number of load reversals until fracture for friction stir welded specimens.

The stress-life data for the large specimens tested under load control is plotted in Fig. 4. The strain controlled data (transformed) and the European recommendations (6) are also included in this figure.

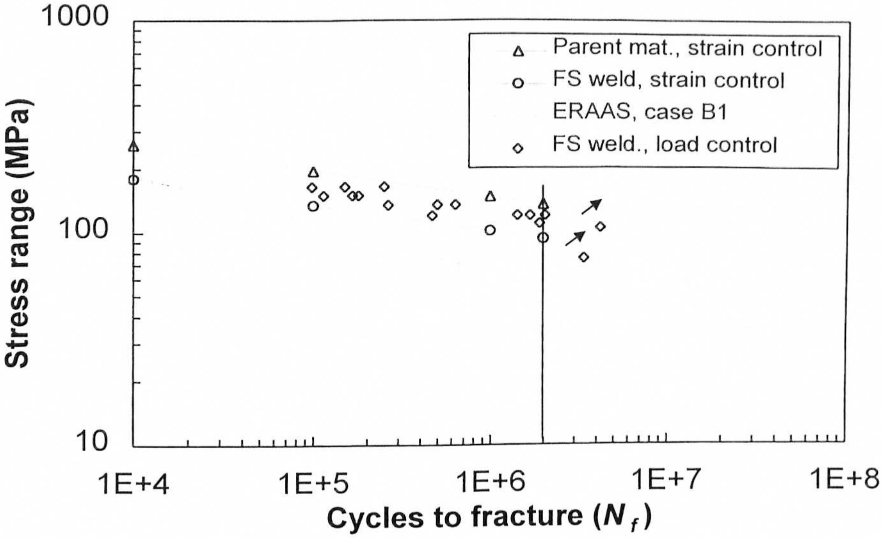

Fig. 4 Stress-life for friction stir welded specimens compared with the European recommendations.

Table 4 Material parameters for cycilc and monotonic behaviour.

Material	R_m	$R_{p0.2}$	ε	$E_{cycl.}$	K	n	K′	n′	σ'_f	b	ε'_f	c	$(2N)_t$	$\sigma_{r,char.}(R=-1)$
	MPa	MPa	%	GPa	MPa	-	MPa	-	MPa	-	%	-	cycles	MPa,(N=2E6
Parent	302	287	8,0	70	315	0,015	383	0,044	630	-0,11	1,05	-0,87	504	217
FS weld	223	148	4,9	70	324	0,13	363	0,089	406	-0,10	0,09	-0,62	191	149

4. DISCUSSION

Reduction parameters are commonly given in standards for the HAZ softening in various alloys and tempers, EN draft (15) calls this factor k_{HAZ}. EN gives different values for MIG and TIG welds. It is found that the experimentally observed softening is larger than that described by the standards. Three of four values of k_{HAZ} are non-conservative in the EN. The property data in the standard is very conservative though, which in the end gives low allowable strength values for welded aluminium alloys. The test material is heat treated to the T5 condition but does also meet the specifications on strength for the T6 temper. The EN shows good agreement with the experimental results for the T6 temper. FS welding is not considered, and this method gives higher HAZ strengths than MIG.

Post-weld material gain in strength, TIG welded joints show strengths of about 70 % of the parent metal strength and FS welded material 86 %. This possibility to increase the capacity of joints should be examined further.

The fatigue performance of FS welded joints are very good, both kinds of tests included in this paper show strengths well above the recommended values.

CONCLUSIONS

- TIG welding introduced more heat into structures than MIG- and friction stir (FS) weldin The HAZ width in TIG welds were twice as large as MIG welded ones, 20 mm compared t mm. FS welding develops the smallest HAZ of the welding processes compared herein, 8 mm.
- Friction stir welding showed the highest strength of the studied welding processes, an avera of 74 % of the parent metal strength in the as-welded condition was found.
- The observed HAZ softening is less than that given in the European (EN) standards.
- The EN gives one HAZ width that is valid for material thickness from 0 to 6 mm, this step-b step correlation gives conservative values both for MIG and TIG welding.
- A second ageing after welding improves the strength of welded joints considerably, 20 % w found. Post TIG weld aged material showed a tensile strength of 207 MPa or 69 % of the pare metal strength. Post FS weld aged material reached an average tensile strength of 260 MPa or % of the original strength.
- Post-weld ageing reduced the width of the HAZ and the appearance of the soft zone chang from being one wide ditch reaching over the whole HAZ, including the weld zone, to two narro ditches on either side of the weld zone.
- The fatigue strength of FS welded joints is very high compared to the recommendations av able today

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REFERENCES

1 Welding Aluminium, Theory and Practice, The Aluminum Association, Washington, 1991

2 S. Kou, Welding Metallurgy, John Wiley & Sons, 1987

3 C. J. Dawes, An Introduction to Friction Stir Welding and its Development, Welding a Metal Fabrication, pp. 13-16, January, 1995

4 O. T. Midling, Material Flow Behaviour and Microstructural Integrity of Friction Stir Bu Weldments, The 4th International Conference on Aluminium Alloys, Atlanta, USA, 1994

5 Draft European Standard, document 132 N 266, Wrought Al. and Al. Alloy-Extruded Rod/B Tube and Profile- Part 2: Mechanical Properties, 1991

6 European Recommendations for Aluminium Alloy Structures Fatigue Design (ERAA ECCS, General Secretariat, Ave. des Ombrages, 32/36 bte 20, B-1200 Brussels, 1992