INFLUENCE OF MICROSTRUCTURE AND WELDING PARAMETERS ON MICROCRACK FORMATION AND FATIGUE PROPERTIES

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Abstract

Experimental extruded 6061 alloy profiles in the T5 temper have been arc welded with 4043 and 5356 filler metals and various welding powers. Two extreme initial microstructures were tested : fibrous unrecrystallized and recrystallized with coarse grains.
Fatigue tests on tension/compression specimens show that the fatigue life is higher in average when using the 4043 filler metal. The combination of 5356 filler metal, coarse grain size in the parent metal and high welding power decreases the fatigue life. The influence of microstructure is significant only at high R ratio. With both filler metals, some microcracks can be observed in the heat affected zone, especially for the coarse grain microstructure. Using a fracture mechanics approach, experimental results can be rationalised.

Introduction

The choice of welding parameters, filler metal and welding power, taking into account the microstructure of the base material, is an issue regarding the application of aluminium in welded structures.

It has been shown that the use of AlMg5 filler metal results in a higher tendency to form grain boundary openings than the use of AlSi5 filler metal, especially when coarse recrystallized grains are present in the edge to be welded [1,2]. The fatigue resistance of welds was somewhat higher with the AlSi5 filler metal than with the AlMg5 filler metal. However, in all cases the fatigue strength clearly exceeded the requirements of codes and specifications [3]. The fatigue study dealt with alloys having low and large excess of silicon. Excess silicon is reported to enhance liquation cracking [3,4]. The mean stress chosen in [3] was rather high : R= 0.5.

The purpose of the present study is to investigate the effect of filler metal (4043 and 5356) on microstructure and fatigue properties of welds made with a balanced alloy (6061). The effect of the following parameters are tested : microstructure of base material (unrecrystallized and coarse recrystallized) ; welding power (normal and high) ; load ratio R (0.1 and -1).

Experimental methods

Welds were made in the edge of an extruded profile of 4 mm thickness (Fig. 1).

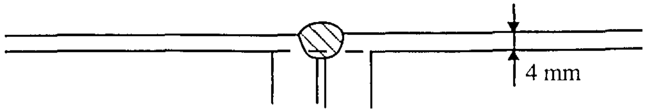

Figure 1. Configuration of the weldment

The composition of the base metal is given in table I.

Table I. Composition of the 6061 alloy

element	Si	Fe	Cu	Mn	Mg	Cr
wt%	0,55	0,21	0,17	0,08	0,93	0,11

Two different microstructures were obtained after adequate lab processing (Fig. 2) :
- unrecrystallized, but with some coarse recrystallized grains ;
- recrystallized with coarse grains (about 1 mm).

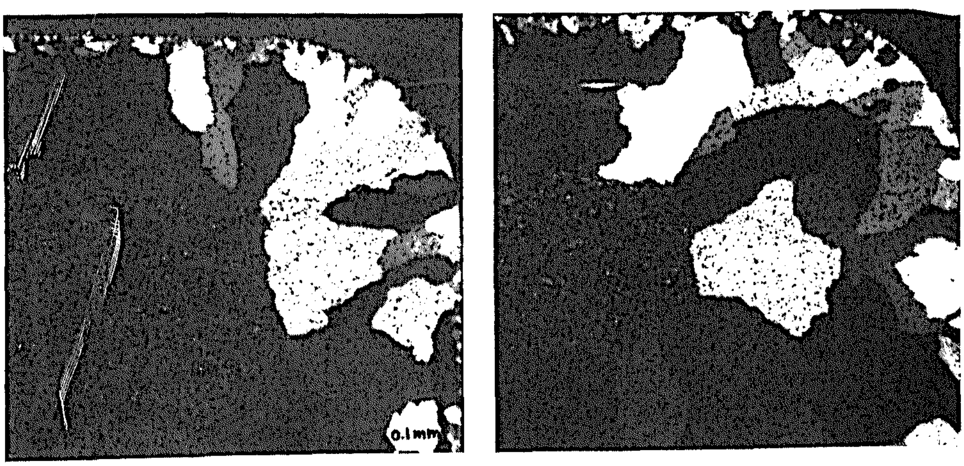

Figure 2. Microstructure of the unrecrystallized (left) and recrystallized (right) profiles

MIG welding was performed with a classical Miller source, with the parameters given in table II.

Table II.Welding parameters

	High power		Low power	
Filler metal	5356	4043	5356	4043
Intensity (A)	220	217	196	174
Voltage (V)	24,4	23,8	21,4	22,4
Welding speed (m/min)	0,48	0,50	0,45	0,37
Fill speed (m/min)	15,5	11,5	13,8	8,91
Weld section area (mm^2)	56	46	45	44
Dilution rate	0,35	0,21	0,19	0,17

Axial fatigue tests were runned on a AMSLER electro-magnetic machine at 120 Hz. The stress amplitude $\Delta\sigma$ was chosen in order to produce fracture after about 10^6 cycles : $\Delta\sigma$ = 140 MPa at R = -1 and $\Delta\sigma$ = 108 MPa at R = 0.1.

Results

Weldments

The weld geometry can affect the fatigue performance. Therefore, the ratio between the height of the weld bead above the profile surface (S) to the weld width (l) was determined, as well as the angle θ of the weld bead surface to the profile surface at their intersection (Table III).

Table III. Weld bead geometry.

	High power		Low power	
filler metal	5356	4043	5356	4043
S/l	0,16	0,04	0,10	0,05
θ	154°	175°	163°	170°

According to Table III, the welds produced fall in the most favorable category with respect to fatigue performance [3].

Examination by optical microscopy reveals that microcracks are formed in the HAZ at the border of the bead (Fig. 3). In the unrecrystallized material, some microcracks are found, the length of which is less than 0.3 mm. These microcracks were generally located at the few recrystallized grains boundaries (see also [5]). In the coarse grain material, microcracks are somewhat larger : their lengths range between 0.3 mm and 0.7 mm. The longest cracks were observed when using high welding power and 5356 filler metal. The largest microcracks penetrate the bead at a depth of about 0.2 mm, depending on the microstructure of the bead.

We have found microcracks in the welds made with both filler metals : Al-Si (4043) and Al-Mg (5356).

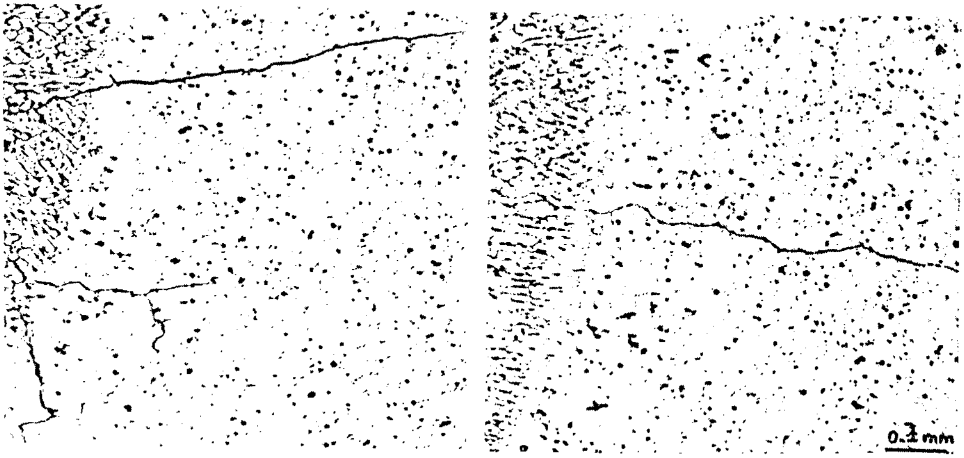

Figure 3. Microcracks in samples welded with 4043 (left) and 5356 (right) ; high welding power and coarse grained base metal.

Tensile properties

The tensile properties of the welds are given in Table IV. Higher yield strength (YS) values are obtained with the 4043 filler metal, which is not usual. The explanation of this peculiar result has not been found. Note that the YS measured in a tensile test results from the deformation of layers having various properties (HAZ, bead). So, the difference in YS does not mean necessarily a difference in the stress at onset of plastic deformation. It might rather result from a difference in the HAZ width.

The UTS value is 10 MPa higher with the unrecrystallized base metal. This result is expected since the fracture occurs at 10 mm of the bead, in the base metal (the UTS is higher for an unrecrystallized metal than for a recrystallized metal, whatever the grain size is).

Table IV. Mechanical properties after welding

	gage length 45 mm	High power		Low power	
		5356	4043	5356	4043
coarse grain base metal	UTS (MPa)	206	206	205	205
	YS (MPa)	113	123	115	131
	El (%)	10	8	9	8
unrecrystallized base metal	UTS (MPa)	219	217	217	216
	YS (MPa)	121	134	113	131
	El (%)	10	7	9	7

Fatigue properties

The fatigue life obtained are plotted in figure 4 in comparison with the ECCS recommendations [3]. It is seen that the results are above the design curve in all cases.

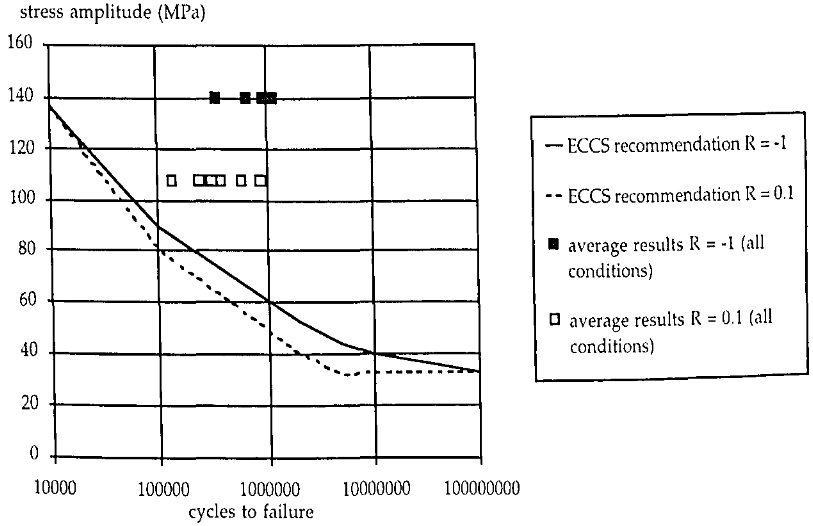

Figure 4. Comparison of the fatigue life obtained in the present study to the ECCS recommendations [3], at R = -1 (above) and R = 0.1 (below).

The effect of welding procedure and microstructure is illustrated in Figure 5. It appears that :

- The average fatigue life is higher when using the 4043 filler metal than when using the 5356 filler metal.
- The combination of 5356 weld metal, high welding power and coarse recrystallized microstructure gives the poorest fatigue results.
- The effect of microstructure (fibrous or coarse grained recrystallized) is significant only at high R ratio (R = 0.1).

Fractographic examination reveals that the fracture surface is located generally near the weld bead / HAZ border. Other locations of the fracture surface are observed for the highest fatigue lifes. These correspond to the use of the 4043 filler metal (Table V).

The fracture initiation is located at the surface of the specimen in almost all cases. Inner initiation sites are observed on some fracture surfaces. Coarse grains are present at these inner initiation sites (except in one case), even for the unrecrystallized specimens (Table V). As written above, some recrystallized grains exist in the unrecrystallized material.

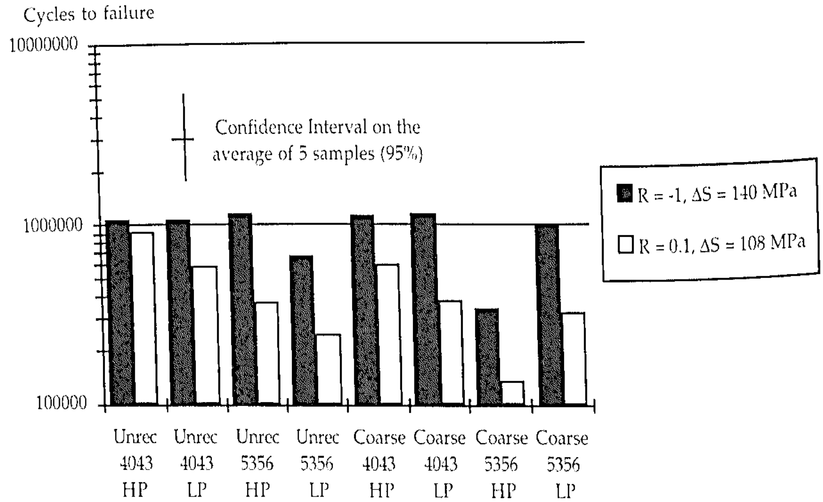

Figure 5. Fatigue life obtained for the different welding conditions (filler metal) and power (H = high and L = low), and for the two microstructures (unrecrystallised and coarse grained recrystallised).

Table V. Location of the fracture surface (majority of 5 samples tested). The number of * indicates the number of identified inner initiation sites among the 5 samples.

R ratio	microstructure	High power		Low power	
		5356	4043	5356	4043
-1	coarse grain base metal	Bead border***	in	Bead border	in
	unrecrystallized base metal	Bead border	out	Bead border	Bead border*
0.1	coarse grain base metal	Bead border**	in*	Bead border	Bead border**
	unrecrystallized base metal	Bead border	in	Bead border	Bead border**

Discussion

It appears that the fatigue life is higher when using the 4043 filler metal. Note also that all fractures located elsewhere than at the bead/HAZ border were obtained with the 4043 filler metal (but some of the 4043 welds occurred at the bead/HAZ border). It has been shown that the 4043 filler metal gives a smoother transition from bead to profile surface (Table II). However, no correlation was found between the fatigue life and the parameters listed in Table II.

Microcracks were found with both filler metals, and high fatigue lives were obtained for presumably micro-cracked specimens. Thus, the presence of microcracks is not directly related to the fatigue life. But some comments can be made when seperating the results obtained at the different R ratios.

R = -1

Almost all cases give similar fatigue performance (Figure 5). Only the combination of high power, 5356 filler metal and coarse grains results in a significantly lower fatigue life.

Except in the latter case, the fracture initiates at the surface of the specimens. As the surface microstructure is similar for both base metals, it is normal to observe no influence of the base metal.

The cracks observed are about 0.5 mm long. Considering only the tensile portion of the stress cycle (70 MPa), the variation of the effective stress intensity factor ΔK can be estimated roughly (to evaluate the effective ΔK, one considers only the part of the stress cycle during which the crack is open):

$$\Delta K = 2/\pi \; \Delta\sigma \sqrt{\pi a} = 1.8 \text{ MPa}\sqrt{m}$$

As the ΔK at threshold for short fatigue cracks is of the order of magnitude of 2 MPa$\sqrt{m}$ [6], one can understand that the inner microcracks are not harmful.

In the peculiar case of 5356 filler metal, high welding power and coarse grains, it is possible that the threshhold is just exceeded, as the largest microcracks are found in this case. This would explain the fact that 3/5 samples failed from an inner initiation site.

R = 0.1

In this case, the highest fatigue lives are obtained for the welds having the highest yield stress, which can be related to the fact that the maximum fatigue stress (120 MPa) is close to the yield stress (Table IV).

Taking the same argument as previously, the initiation should take place much more often inside the specimen, rather than at the surface. This is actually observed, the inner initiation sites correspond to a place where a coarse grain is present (even in the unrecrystallised material). In this case, ΔK for a 0.5 mm crack can be evaluated ($\Delta\sigma$ = 108 MPa):

$$\Delta K = 2.8 \text{ MPa}\sqrt{m}$$

Of course, the evaluation of ΔK is very rough, but the qualitative argument developed seems to be valid : the microcracks are only harmful when the corresponding effective stress intensity factor variation is sufficient to grow a crack. The corresponding stress amplitude is about 3 times the stress amplitude used for design of long life structures.

Conclusion

- The 4043 filler metal is beneficial when considering the fatigue resistance of 6061 welds, compared to 5356. This cannot directly be related to the existence or not of microcracks since microcracks are found with both filler metals, especially when coarse grains are present.
- The combination of 5356, coarse grains and high welding power gives the poorest fatigue lives, yet well above the design curves of the ECCS.
- There is no effect of the base metal microstructure at R = -1. At R = 0.1, the coarse grained material gives lower fatigue lives. This can be explained by an argument based on fracture mechanics. It follows from this argument that the microcracks observed are not harmful in the stress range used for design of long life structures.

References

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