FATIGUE ANALYSIS IN AlMgSi WELDMENTS

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Abstract. This paper is concerned with the fatigue behaviour of T6 heat-treated AlMgSi1 aluminium alloy weldments. The fatigue tests were carried out using two types of welded joint: T and single lap. The main objective of this research was to study the efficiency of fatigue life improvement techniques, such as post-weld heat treatment and weld toe's burr dressing, for thin joints manufactured in a 6000 series aluminium alloy. A fatigue strength improvement was obtained with both the post-weld heat treatment and the burr dressing, being this fact discussed for both geometries. Finally, a single lap joint series was tested under bloc variable amplitude loading and the correspondent experimental results were modelled with the Miner's rule. A good agreement was verified between these results and the *S-N* curve obtained for constant amplitude loading.

1. INTRODUCTION

Due to the fact of combine a relatively high strength, good corrosion resistance and high toughness with good formability and weldability, the aluminium alloys, in particular the 6000 series, are more and more frequently used in order to attain a reduction of weight, mainly in automotive type structural applications. However, the existence of a geometrical discontinuity associated with high residual stresses turns the welded joint a critical point in what concerns to structural strength. In this context, the improvement of weldment fatigue strength is a procedure of crucial importance, which is generally done by alteration of residual stress levels or improvement of weld toe's geometry.

From the constant amplitude fatigue tests, the following expression for the S-N curve is obtained:

$$\Delta S^m N_r = C \qquad (1)$$

where ΔS is the nominal stress range, N_r is the number of cycles to rupture, and m and C are, respectively, the exponent and the coefficient of the *S-N* curve.

In situations of bloc variable amplitude loading, the Miner's rule [1] is usually applied. This rule assumes that the damage accumulates linearly, occurring fatigue rupture when the total damage D equals the unity:

$$D = \sum \frac{N_j}{N_{r,j}} \qquad (2)$$

where N_j is applied the number of cycles for a given stress range, and $N_{r,j}$ is the correspondent number of cycles to rupture, in agreement with (1). Neglecting the effect of the fatigue limit, the substitution of (1) in Miner's rule (2) enables the definition of an equivalent stress range ΔS_{eq}, expressed by [2]:

$$\Delta S_{eq} = \left(\frac{\sum N_j \Delta S_j^m}{\sum N_j} \right)^{\frac{1}{m}} \qquad (3)$$

where N_j is the applied number of cycles at a stress range ΔS_j and m is the *S-N* curve exponent.

The main objectives of this paper are: (i) to analyse the effect of weld toe's burr dressing in a T type welded joint, (ii) study the effect of a post-weld heat treatment T6 in the fatigue behaviour of a single lap type welded joint and (iii) evaluate the accuracy of the Miner's law in the description of the fatigue life of post-weld heat-treated single lap joints tested under bloc variable amplitude loading.

2. EXPERIMENTAL DETAILS

An initially T6 heat-treated AlMgSi1 (6082) aluminium alloy was used in this work. This alloy's chemical composition and mechanical properties are presented in tables 1 and 2, respectively.

Table 1. AlMgSi1 alloy's main chemical composition (weight. %).

Si	Mg	Mn	Fe	Cr	Zn
0.7-1.3	0.6-1.2	0.4-1	0.5	0.25	0.2

Table 2. T6 heat-treated AlMgSi1 alloy's mechanical properties.

Ultimate tensile strength, σ_{UTS} [MPa]	300
Monotonic yield strength, σ_{YS} [MPa]	245
Young's modulus, E [GPa]	74
Poisson's coefficient, ν	0.32
Cyclic strain hardening exponent, n'	0.064
Cyclic strength coefficient, K' [MPa]	443
Fatigue strength exponent, b	-0.0695
Fatigue strength coefficient, σ'_f [MPa]	485
Fatigue ductility exponent, c	-0.827
Fatigue ductility coefficient, ε'_f	0.773

Two distinct series of welded joint, namely T and single lap, were performed. Both type of specimens were machined from 3 mm thick sheets, which were previously welded by the manual TIG process using the AlMg5 (5356) alloy as filler metal. Figures 1 and 2 illustrate the general dimensions of the T and single lap specimens, respectively.

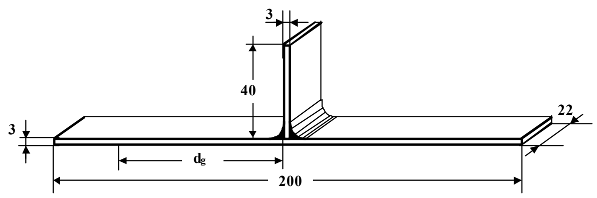

Fig. 1. T joint details.

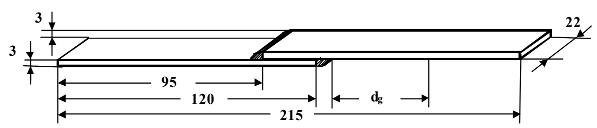

Fig. 2. Single lap joint details.

All the fatigue tests were performed, in load control with a 25 Hz frequency, using a computer-controlled servo-hydraulic INSTRON machine with a 100 kN capacity.

Two main series of welded specimens fatigue tests were carried out: (i) in T specimens and (ii) in single lap specimens. In both situations, the grips were attached at a 50 mm distance d_g from the weld toe (figs. 1 and 2).

Two different types of T joint series were performed: one of as-welded specimens and another of burr-dressed specimens. Both these series were tested under constant amplitude tests with a zero nominal stress ratio R_S.

Two different types of single lap joint series were performed: one of as-welded specimens and another of post-weld T6 heat-treated specimens. The T6 heat treatment consisted, initially, in a phase of solution performed at 530ºC for 45 min, followed by quenching in water and, finally, an ageing phase at 165ºC for 10h [3]. Both the as-welded and a fraction of the T6 heat-treated specimens were tested under constant amplitude tests with a zero nominal stress ratio R_S. The remaining fraction of T6 heat-treated specimens was separated in two series, which were tested under two different types of bloc variable amplitude loading, one with a constant maximum load P of 6 kN and another with a constant minimum load P of 0 kN.

Table 3 reports some information related to all tested series.

Table 3. Condition of the tested specimens.

Series	Type	Condition	Type of load
1	T	as-welded	C.A. ($R_S = 0$)
2	T	Burr-dressed	C.A. ($R_S = 0$)
3	s. lap	as-welded	C.A. ($R_S = 0$)
4	s. lap	T6 heat-treated	C.A. ($R_S = 0$)
5	s. lap	T6 heat-treated	B.V.A.C. P_{min}
6	s. lap	T6 heat-treated	B.V.A.C. P_{max}

In order to characterise the local weldments' geometry, several specimens of each type of joint were randomly chosen and sliced. Subsequently, the slices' weld toe radii of curvature, r_c, were measured from mathematical manipulation of profile points obtained by the use of a Mitutoyo projector, being 2.97 mm and 0.7 mm the average radius values, and 1.11 mm and 0.42 mm the standard deviation values detected for the T and single lap joints, respectively.

Finally, some SEM observations of the initiation and final rupture locals were made in single lap joints.

3. RESULTS AND DISCUSSION

Table 4 presents the S-N curves of the constant amplitude fatigue tests, which were obtained from regression analysis assuming log (N_r) as the dependent variable.

Table 4. Regression equations for CA S-N data.

Series	Type	Regression equation
1	T	$\Delta S^{4.8}$ Nr = 4 × 10^{13}
2	T	$\Delta S^{7.0}$ Nr = 8 × 10^{17}
3	single lap	$\Delta S^{4.1}$ Nr = 8 × 10^{11}
4	single lap	$\Delta S^{6.3}$ Nr = 2 × 10^{16}

3.1 As-welded specimens fatigue results

Figure 3 presents the as-welded specimens constant amplitude fatigue results, for a zero nominal stress ratio R_S, of the T and single lap joints. The nominal stress range ΔS is plotted against the number of cycles to rupture N_r. It can be seen that T joints present greater fatigue strength than single lap joints. This fact can be explained by the existence of higher local stress levels in single lap joints, reducing, consequently, the single lap fatigue strength, due to the following reasons: (i) the existence of smaller radii of curvature in the single lap joints (mean value = 0.7 mm, standard deviation = 0.42 mm) than in T joints (mean value = 2.97 mm, standard deviation = 1.11 mm), (ii) the existence of a static tension stress due to geometrical deformation induced by the gripping of single lap joints, which corresponds to an initial bending load [4].

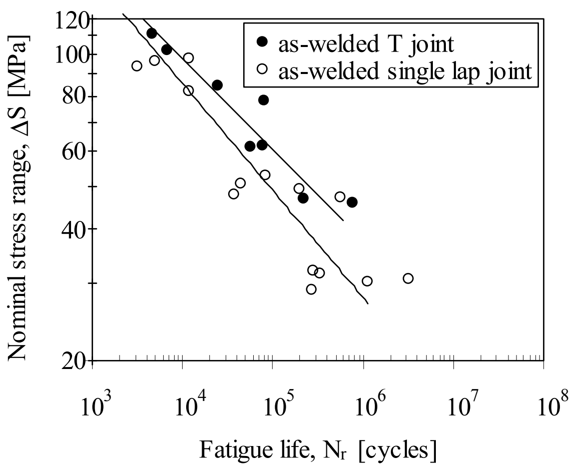

Fig. 3. As-welded joints' experimental fatigue results.

3.2. Influence of the post-weld treatments on fatigue lives

3.2.1. T joints

Figure 4 presents the results of the constant amplitude fatigue tests of the T joints in the as-welded and in the burr-dressed conditions, for a zero nominal stress ratio R_S. The nominal stress range ΔS is plotted against the number of cycles to rupture N_r. An improvement of fatigue life was obtained by the burr dressing in comparison with the as-welded T specimens, namely an improvement of the stress range of about 18 % for a crack initiation life of 10^5 cycles. This is mainly due to the fact that burr dressing operation not only promotes the removal of weld toe's surface defects, leading to a higher initiation fatigue phase, but also gives rise to greater weld toe's radii of curvature and, consequently, to lower local stress levels.

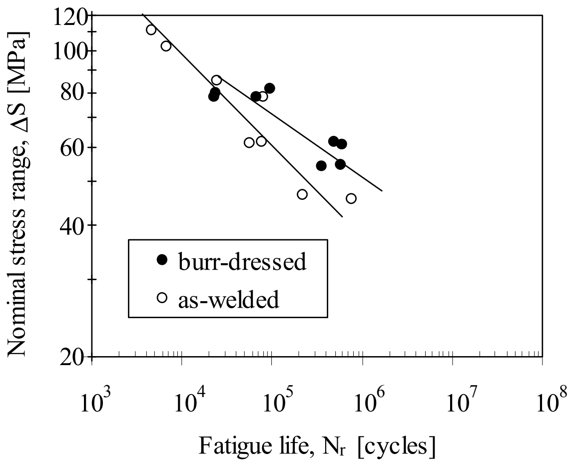

Fig. 4. T joints' experimental fatigue results.

3.2.2. Single lap joints

Figure 5 presents the results of the constant amplitude fatigue tests of single lap joints in the as-welded and in the heat-treated conditions, for a zero nominal stress ratio R_S. The nominal stress range ΔS is again plotted against the number of cycles to rupture N_r.

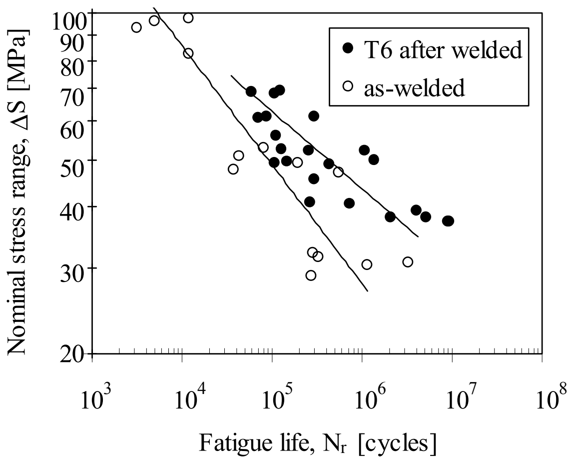

Fig. 5. Single lap joints' experimental fatigue results.

An improvement of fatigue life was obtained by the T6 heat treatment in comparison with the as-welded specimens, namely an improvement of the stress range of about 57 % for a fatigue life of 10^6 cycles.

The beneficial effect of the T6 heat treatment on the fatigue strength of single lap joints can be explained by two different mechanisms: (i) the relief of tensile residual stresses originated by the welding process, which accelerate the crack initiation and reduce fatigue life by the increase of local mean stresses, (ii) an increase in fatigue strength of the HAZ, due to the recovery of the tensile strength of the welded specimens (σ_{YS} = 106 MPa, σ_{UTS} = 140 MPa) to the original strength of the parent metal (σ_{YS} = 245 MPa, σ_{UTS} = 300 MPa). This fact is illustrated in figures 6 and 7, where it can be observed that the rupture zone for the heat-treated joint presents dimples of minor dimension than for the as-welded joint, which is associated to a greater mechanical resistance.

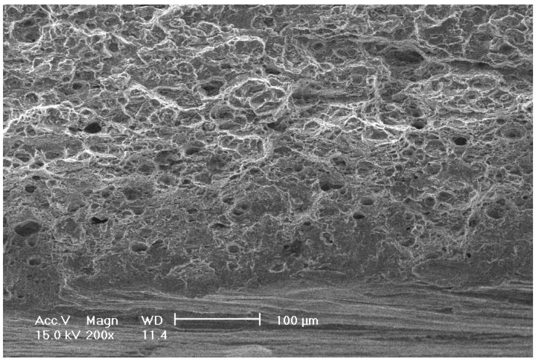

Fig. 6. SEM micrograph of the as-welded joint's rupture zone.

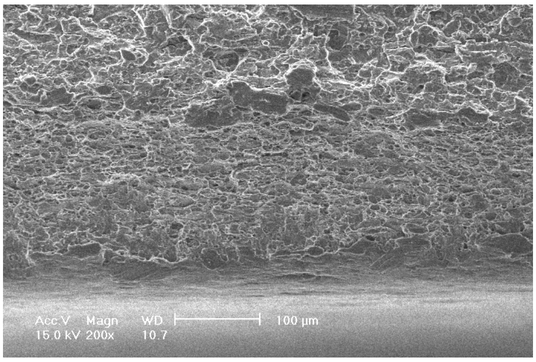

Fig. 7. SEM micrograph of the heat-treated joint's rupture zone.

It is worthwhile to notice that some investigators have not verified a T6 heat treatment fatigue strength improvement in 6000 Al-alloys series [5].

A multiple initiation of fatigue cracks was observed in the welded specimens, being this fact illustrated, for the particular case of a single lap joint, in figure 8.

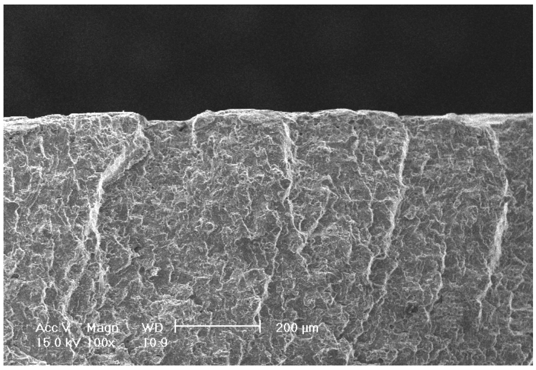

Fig. 8. Multiple initiation in single lap joints.

3.3. Fatigue life results for bloc variable amplitude loading

In accordance with (3), the bloc variable amplitude fatigue results are presented in figure 9, together with the constant amplitude heat-treated single lap joint ones. It can be concluded that the data of bloc variable amplitude fatigue present less scattering than the constant amplitude ones. It's also verified that the constant maximum load *P* fatigue results show less scattering than the constant minimum load *P* ones. These facts can be explained by the tendency of scatter in periodic overstrain data to be minor than in constant amplitude data [6]. It can also be observed that the bloc variable amplitude equivalent data follow the constant amplitude curve trendline. Therefore it can be concluded that (3) gives an adequate description of the variable amplitude effects.

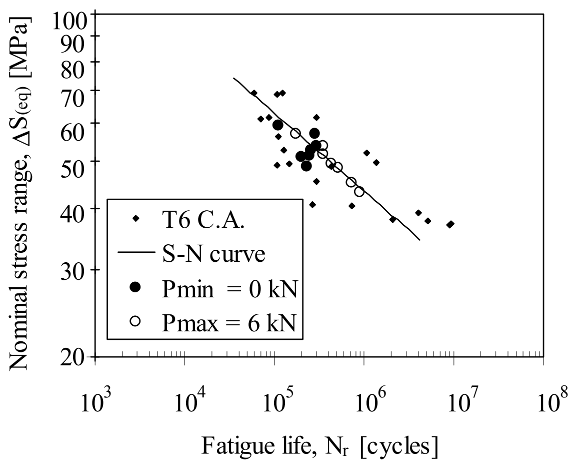

Fig. 9. Bloc variable amplitude fatigue results.

An equivalent way of represent the bloc variable fatigue results is shown in figure 10, where the predicted lives, N_{pr}, were obtained by the substitution of ΔS_{eq} in (1). Two straight lines $N_{pr} = 2N_r$ and $N_{pr} = 0.5N_r$ were also plotted and used as criterion limits of prediction exactness. The predicted lives are almost all included between these limits, indicating that this method gives reasonable predictions [6].

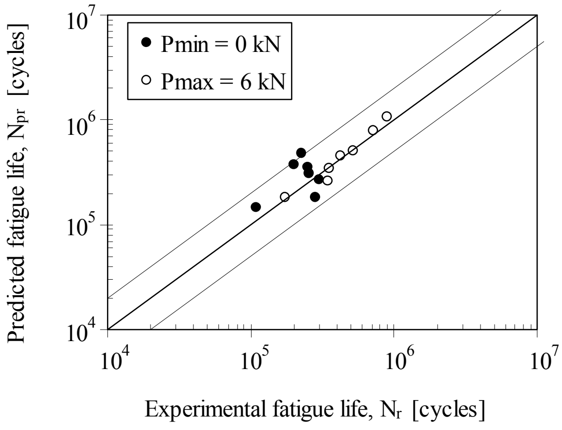

Fig. 10. Predicted life *vs.* experimental life.

4. CONCLUSIONS

From the experimental fatigue behaviour study of AlMgSi aluminium alloy weldments, the following conclusions can be drawn:

1. The burr dressing treatment improved the fatigue strength of the T welded specimens. An improvement of about 18 % of the stress range was attained for a crack initiation life of 10^5 cycles.

2. The T6 heat treatment significantly improved the fatigue strength of the single lap welded specimens. An improvement of about 57 % of the stress range was attained for a crack initiation life of 10^6 cycles.

3. The results of bloc variable amplitude fatigue tests present less scattering than the constant amplitude ones. The constant maximum load *P* fatigue results show less scattering than the constant minimum load *P* ones.

4. The bloc variable amplitude equivalent data follow the constant amplitude curve trendline, giving the equivalent stress range an adequate description of the variable amplitude effects.

5. The Miner's rule conducted to reasonable life predictions.

5. REFERENCES

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