Available online at www.sciencedirect.com

ScienceDirect

Procedia Structural Integrity 25 (2020) 438–444

Structural Integrity
Procedia

www.elsevier.com/locate/procedia

1st Virtual Conference on Structural Integrity - VCSI1

Cyclic plastic behaviour of 7075 aluminium alloy

F. Nogueira[a]*, J. Cunha[a], A. Mateus[a,b], C. Malça[a,c], J.D. Costa[d], R. Branco[d]

[a]Centre for Rapid and Sustainable Product Development, Polytechnic Institute of Leiria, Portugal
[b]Department of Mechanical Engineering, ESTG, Polytechnic Institute of Leiria, Portugal
[c]Department of Mechanical Engineering, ISEC, Polytechnic Institutue of Coimbra, Portugal
[d]CEMMPRE, Department of Mechanical Engineering, University of Coimbra, Portugal

---

Abstract

This paper aims at studying the cyclic plastic behaviour of the 7075-T651 aluminium alloy under fully-reversed strain-controlled conditions. Tests are conducted under strain-control mode, at room temperature, in a conventional servo-hydraulic machine, from smooth samples, using the single step method, with strain amplitudes ($\Delta\varepsilon/2$) in the range ±0.5 to ±2.75%. This material has exhibited a mixed behaviour, i.e. cyclic strain-hardens at higher strain amplitudes ($\Delta\varepsilon/2/>1.1\%$) and cyclic strain-softens at lower strain amplitudes ($\Delta\varepsilon/2<1.1\%$). A linear relationship between the degree of cyclic strain-hardening and the strain amplitude has been established for higher strain amplitudes. Fatigue-ductility and fatigue-strength properties agree with those found in the open literature for the same loading conditions.

Keywords: Low-cycle fatigue; cyclic plastic behaviour, strain-softening, aluminium alloy; 7075-T651

---

1. Introduction

High-strength Al-Zn-Mg-Cu alloys are used in a vast number of structural applications, mainly due to their balance properties, in particular the excellent strength-to-weight ratio, attractive specific stiffness, good corrosion resistance, and high toughness [1]. Although structural applications are usually designed in such a way that materials

---

* Corresponding author.
E-mail address: filipe.t.nogueira@ipleiria.pt

10.1016/j.prostr.2020.04.049

Nomenclature

b	fatigue strength exponent
c	fatigue ductility exponent
CS	cyclic strain
CH	cyclic hardening
E	Young's modulus
N	number of cycles
N_f	number of cycles to failure
$\Delta\varepsilon/2$	strain amplitude
$\Delta\sigma/2$	stress amplitude
ε	strain
ε_f'	fatigue ductility coefficient
σ	stress
σ_f'	fatigue strength coefficient
σ_{YS}	yield strength
σ_{UTS}	ultimate tensile strength
ν	Poisson's ratio
$2N_f$	Number of reversals to failure

only deform in an elastic manner, local plastic deformation can occur at the geometric discontinuities, making them susceptible to fatigue failure. As far as the fatigue life prediction is concerned, the most popular approaches have been established via stress-based, strain-based, or energy-based relationships. Particularly the stress-based and the strain-based approaches, perhaps because of their simplicity, are among the most used. Thus, the full understanding of cyclic plastic behaviour is a major asset in the development of durable and reliable fatigue life predictions [2-5].

This paper aims at studying the cyclic plastic behaviour of the 7075-T651 aluminium alloy under strain-control mode using standard smooth cylindrical specimens. Tests are conducted under fully-reversed conditions, with a strain ratio equal to -1, at strain amplitudes ($\Delta\varepsilon/2$) lying between ±0.5 and ±2.75%. From the experimental data, the cyclic stress-strain response is studied, and the degrees of cyclic strain-hardening and cyclic strain-softening are evaluated. Finally, the fatigue-strength and the fatigue-ductility properties are accounted for and compared with the results available in the open literature for the same loading conditions.

2. Experimental procedure

The tested material was a commercial 7075-T561 aluminium alloy. The main chemical composition, in weight percentage, as well as the main mechanical properties and listed in Table 1 and Table 2, respectively. From the as-received plates, both circular cross-section samples with 15mm-long and 8mm-diameter gauge sections (see Figure 1), and circular cross-section samples with 19mm-long and 6mm-diameter gauge sections were machined. The tests were conducted under strain-control mode, up to total failure, in a DARTEC servo-hydraulic testing machine, at

Table 1. Chemical composition of the tested 7075-T651 aluminium alloy (wt.%).

Zn	Mg	Cu	Si	Fe	Mn	Al
4.89	2.12	1.52	0.33	0.007	0.09	Bal.

Table 2. Main monotonic mechanical properties of the tested 7075-T651 aluminium alloy.

Property	Yield strength, σ_{YS}	Tensile strength, σ_{UTS}	Young's modulus, E	Poisson's ratio	Elongation at break
Value	503 MPa	572 MPa	71.7 GPa	0.306	11%

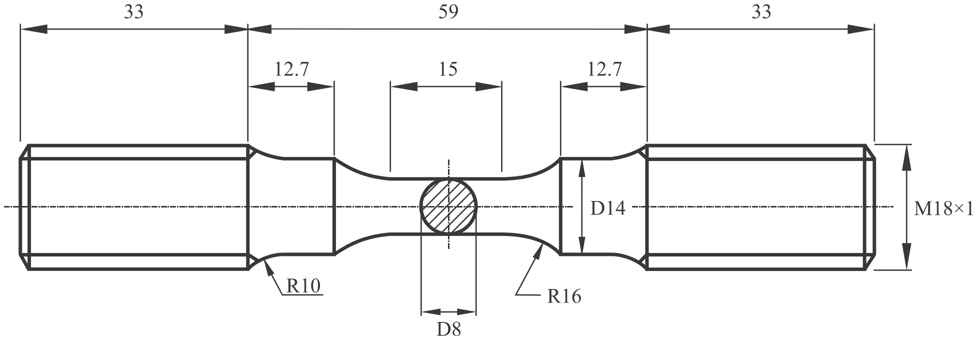


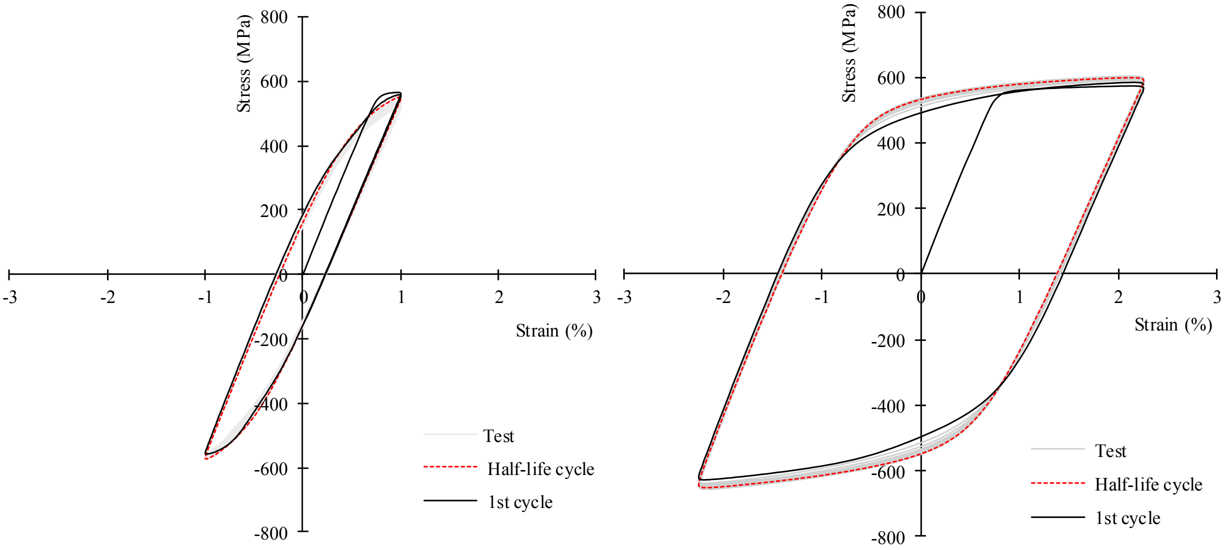
Fig. 1. Specimen geometry used in the fatigue campaign defined in accordance with the ASTM E606 standard.

room temperature, with strain amplitudes lying between 0.5% and 2-75%, and a constant strain rate (dε/dt) equal to 8×10^{-3} s^{-1}. The former geometry was used at higher strain amplitudes (Δε/2≥1.5%), while the latter was used at lower strain amplitudes (Δε/2<1.5%). Stress-strain data were acquired from an electrical extensometer clamped directly to the specimen via two separated knife-edges.

3. Results and discussion

Figure 2 exhibits typical examples of the cyclic stress-strain response recorded in the low-cycle fatigue tests. The main outcome is that the changes in the hysteresis loop shapes during the tests are relatively tenuous, either at lower strain amplitudes (Figure 2(a)), or at higher strain amplitudes (Figure 2(a)). In the case of Figure 2(a), at Δε/2=1.0%, there is a slight decrease of the maximum tensile stress in an initial stage of the test, which denotes a cyclic strain-softening behaviour; on the contrary, in the case of Figure 2(b), at Δε/2=2.25%, we can identify an increase in the maximum tensile stress, which is sign of cyclic strain-hardening.

These stress variations over the tests can be better inferred in Figure 3. This figure, as can be observed, plots the



(a) (b)

Fig. 2. Examples of the cyclic stress-strain response observed in the experiments for the teste aluminium alloy: (a) Δε/2=1.00%; (b) Δε/2=2.25%.

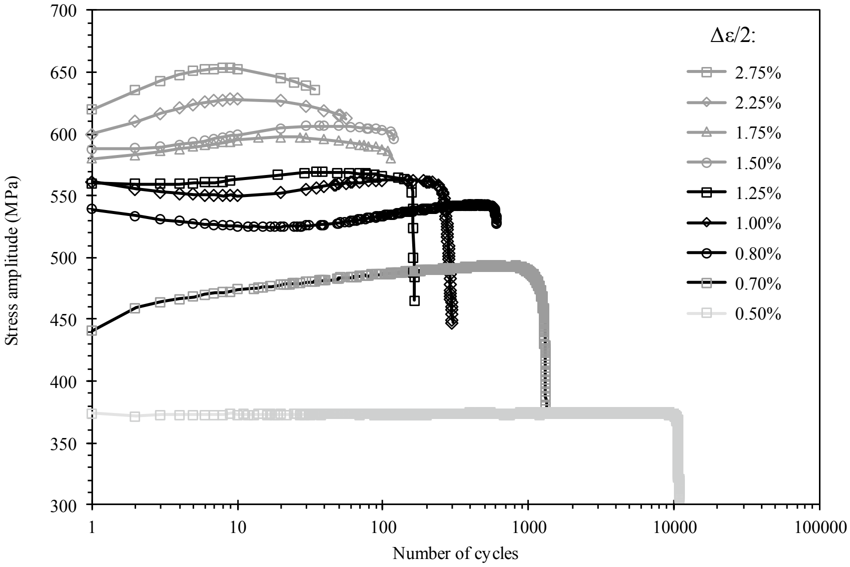


Fig. 3. Examples of the cyclic stress-strain response observed in the experiments for the teste aluminium alloy: (a) Δε/2=1.00%; (b) Δε/2=2.25%.

stress amplitude against the number of cycles at different strain amplitudes. In fact, as suggested in the previous figure, the 7075-T561 aluminium alloy tested here has a mixed behaviour. For higher strain amplitudes, it tendentially cyclic-hardens, and for lower strain amplitude, it tendentially cyclic-softens. In addition, although the mixed behaviour, the cyclic stress response can be divided into three main stages: (i) a rapid initial variation corresponding to 10% of the total life; (ii) a saturated stage that ends at about 90% of the total life; and (c) a final stage characterised by a rapid drop of the stress amplitude until fatigue failure occurs.

The degree of cyclic strain-softening (DS_1) can be accounted for by the following equation

$$DS_1 = \frac{\sigma_{max}^{1st} - \sigma_{max}^{HL}}{\sigma_{max}^{HL}} \tag{1}$$

where σ_{max}^{1st} is the maximum tensile stress of the first cycle, and σ_{max}^{HL} is the maximum tensile stress of the half-life cycle. An alternative definition for the degree of strain-softening (DS_2) is presented below

$$DS_2 = \frac{\sigma^{M} - \sigma_{max}^{HL}}{\sigma_{max}^{HL}} \tag{2}$$

where σ^M is the tensile stress of the monotonic stress-strain curve for the strain amplitude of the σ_{max}^{HL}. The evolution of the two above-mentioned variables with the strain amplitude is displayed in Figure 4. As far as it can be observed, both approaches lead to similar trends. For strain amplitudes higher than about 1.0% (DS_1) and 1.25% (DS_2), there is a linear correlation between the degree of cyclic strain-softening and the strain amplitude. Note that the negative values associated with this region represent a cyclic strain-hardening behaviour. For lower strain amplitudes, i.e. $\Delta\varepsilon/2<1.0\%$ (DS_1) or $\Delta\varepsilon/2<1.25\%$ (DS_2), the values of DS are close to zero. In this second region, the DS_2-$\Delta\varepsilon/2$ relationship continues to be successful fitted by a horizontal straight line, but the same seems not to be satisfactory for the DS_1-$\Delta\varepsilon/2$ relationship. In the latter case, DS_1 values present some fluctuations.

Strain-based approaches, in essence, establish relationships between the elastic or the plastic strain amplitude and fatigue life. Figure 5 plots the elastic strain amplitude ($\Delta\varepsilon_e/2$) against the number of reversals to failure ($2N_f$) for the tested aluminium alloy. These data, as first proposed by the Basquin, can be fitted in a log-log scale by a straight line, i.e.

$$\frac{\Delta\varepsilon_e}{2} = \frac{\sigma_f'}{E}\left(2N_f\right)^{b} \Leftrightarrow \frac{\Delta\varepsilon_e}{2} = \frac{991.6}{E}\left(2N_f\right)^{-0.092} \tag{3}$$

where σ_f' is the fatigue strength coefficient, and b is the fatigue strength exponent. Here, both unknowns were obtained by linear regression via the least square method. As can be seen in the figure, a high correlation coefficient has been found (r = 0.980). On the other hand, it is also clear that the experimental data as well as the fitted function are quite close to the results found the open literature [5] for this aluminium alloy. Figure 6 displays the relationship

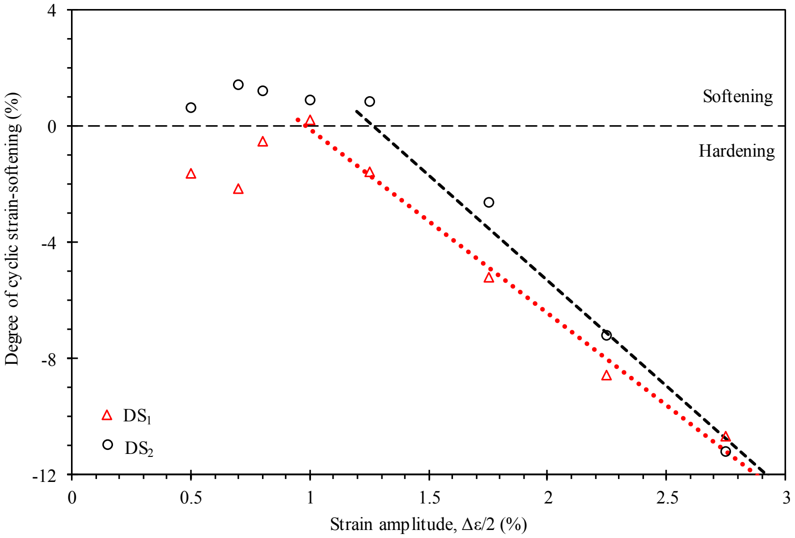


Fig. 4. Degree of cyclic strain-softening for the strain amplitudes tested in the experimental campaign.

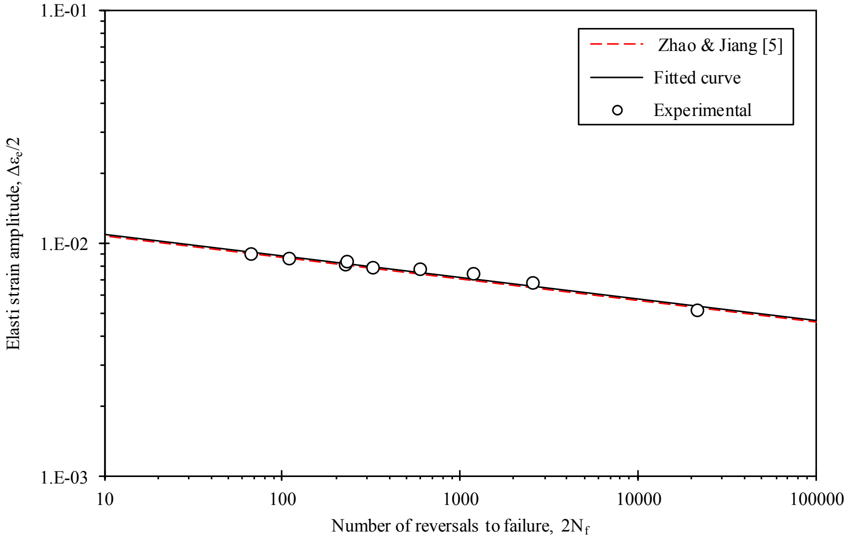


Fig. 5. Elastic strain amplitude versus number of reversals to failure for the tested 7075-T651 aluminium alloy.

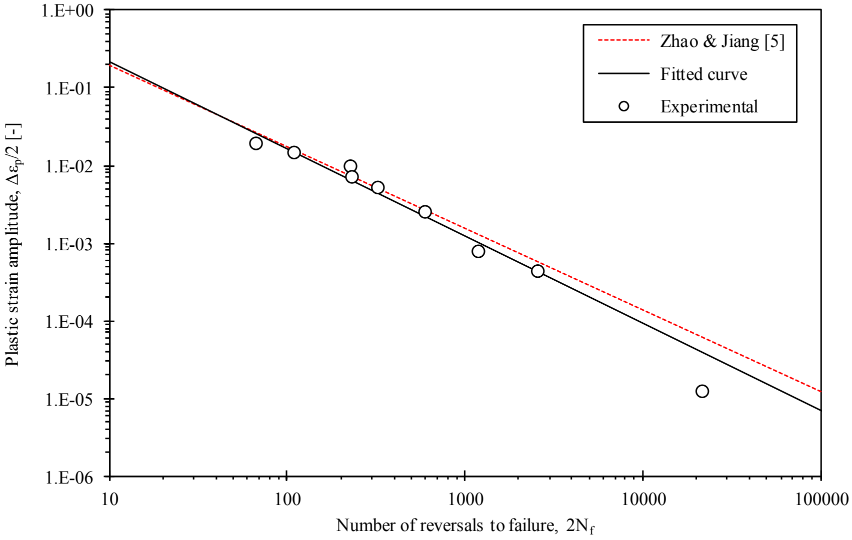


Fig. 6. Plastic strain amplitude versus number of reversals to failure for the tested 7075-T651 aluminium alloy.

between the plastic strain amplitude ($\Delta\varepsilon_p/2$) and the number of reversals to failure ($2N_f$) for the aluminium alloy studied in this research. In the low-cycle fatigue regime, as first observed by Coffin and Manson, the plastic strain amplitude and the number of reversals to failure can be expressed in the following form

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon_f'\left(2N_f\right)^c \Leftrightarrow \frac{\Delta\varepsilon_p}{2} = 2.94\left(2N_f\right)^{-1.123} \tag{4}$$

where ε_f' is the fatigue ductility coefficient, and c is the fatigue ductility exponent. This equation, in a log-log scale, as represented in Figure 6, leads to a straight line. In this study, the fatigue ductility constants were obtained by linear regression using the least square method with a relatively high correlation coefficient (r = 0.986). The comparison of the present results with those published by Zhao and Jiang for the same material show a very good agreement. The fatigue resistance relationship (see Eq. (5)), in terms of total strain amplitude ($\Delta\varepsilon/2$) can be obtained by adding the elastic component (Eq. (3)) and plastic component (Eq. (4)).

$$\frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{991.6}{E}\left(2N_f\right)^{-0.092} + 2.94\left(2N_f\right)^{-1.123} \tag{5}$$

4. Conclusions

This paper has investigated the cyclic plastic behavior of the 7075-T651 aluminium alloy under strain control mode. An experimental fatigue testing campaign has been designed to evaluate the stress-strain response, the degree of strain-softening, as well as the fatigue-ductility and the fatigue-strength properties. The following conclusions can be drawn:

- The cyclic stress-strain response encompasses a rapid initial variation in the stress amplitude which corresponds to 10% of the total life; a saturated stage that ends at about 90% of the total life; and a final stage characterised by a rapid drop of the stress amplitude until fatigue failure occurs;
- Under fully-reversed conditions, for strain amplitudes higher than 1%, a cyclic strain-softening behaviour was observed. In this interval, a linear correlation between degree of cyclic strain-softening and the strain amplitude. On the contrary, at lower strain amplitudes, the degree of softening approaches to zero;

- Fatigue strength and fatigue ductility properties have been evaluated from the experimental data via the least square method with high correlation coefficients. The unknowns of both the Coffin-Manson curve and the Basquin curve are in good agreement with those available in the open literature.

Acknowledgements

The authors would like to acknowledge the sponsoring under the project n.º028789, financed by the European Regional Development Fund (FEDER), through the Portugal-2020 program (PT2020), under the Regional Operational Program of the Center (CENTRO-01-0145-FEDER-028789) and the Foundation for Science and Technology IP/MCTES through national funds (PIDDAC).

This work was also financially supported by the project POCI-01-0247-FEDER-024533 funded by FEDER through COMPETE2020 – "Programa Operacional Competitividade e Internacionalização" (POCI) and by national funds (PIDDAC) through FCT/MCTES. The Foundation for Science and Technology (FCT) and Centro2020 sponsored through the Project references UID/Multi/04044/2019 and PAMI - ROTEIRO/0328/2013 (Nº 022158).

References

1. Heinz, A., Haszler, A., Keidel, C., Moldenhauer, S., Benedictus, R., Miller, W., 2000. Recent development in aluminium alloys for aerospace applications. Material Sciences and Engineering A 280, 102–107.
2. Feng, L, Qian, X., 2018. Low cycle fatigue test and enhanced lifetime estimation of high strength steel S550 under different strain ratios. Marine Structures 61, 343–360.
3. Wu, S., Xu, Z., Yu, C., Kafka, O., Liu, W., 2017. A physically short fatigue crack growth approach based on low cycle fatigue properties. International Journal of Fatigue 103, 185–195.
4. Branco, R., Costa, J.D., Berto, F., Antunes, F.V., 2018. Fatigue life assessment of notched round bars under multiaxial loading based on the total strain energy density approach. Theoretical and Applied Fracture Mechanics 97, 340-348.
5. Zhao, T., Jiang, Y., 2008. Fatigue of 7075-T651 aluminum alloy. International Journal of Fatigue 30, 834–849.