COMPARISON BETWEEN STRAIN-CONTROLLED AND STRESS-CONTROLLED FATIGUE TEST PROCEDURES IN AA7175-T1 ALUMINUM ALLOY

Rodrigo Magnabosco
Professor at Mechanical Engineering Department of "Centro Universitário da FEI" – Av. Humberto A. C. Branco, 3972 – São Bernardo do Campo – SP – BRASIL – 09850-901 – tel# 55-11-43532900 ext. 2173 – rodrmagn@fei.edu.br

Aline Szabo Ponce
Undergraduated student at Mechanical Engineering Department of "Centro Universitário da FEI" – Av. Humberto A. C. Branco, 3972 – São Bernardo do Campo – SP – BRASIL – 09850-901 – tel# 55-11-43532900 ext. 2173 – alineponce@juntos.com

Gigliola Salerno
Undergraduated student at Mechanical Engineering Department of "Centro Universitário da FEI" – Av. Humberto A. C. Branco, 3972 – São Bernardo do Campo – SP – BRASIL – 09850-901 – tel# 55-11-43532900 ext. 2173 – giglia@ig.com.br

Maurício de Carvalho Silva
Graduated student at Escola Politécnica - University of São Paulo – Department of Naval and Ocean Engineering – Professor Mello Moraes Avenue, 2231 – São Paulo – SP – BRASIL – 05508-900 – tel# 3091-5350 ext.253 – carvalho.silva@poli.usp.br

Abstract. *The AA7175 aluminum alloy is widely used in high specific mechanical strength applications; however, to satisfy this demand the mechanical design must consider the fatigue life. This work describes the mechanical behavior (monotonic and cyclic) of AA7175 aluminum alloy, and compares the strain-controlled fatigue tests with stress-controlled ones. Tension tests were conducted in a 250 kN MTS universal machine, and low-cycle (strain-controlled) fatigue tests were conducted in the same equipment, following the ASTM E-606 standard procedure until its final failure, obtaining the total number of cycles to failure for a given strain amplitude. These results allow the determination of the Coffin exponent and the fatigue ductility coefficient, which characterizes the plastic strain influence on fatigue life, and the Basquin exponent and fatigue strength coefficient, related to elastic strain influence on fatigue life. These values were compared with the ones obtained in previous work of fatigue life determination using stress-controlled fatigue tests. It was concluded that strain-controlled fatigue tests are much more reliable than stress controlled ones to determine fatigue life of AA7175-T1 aluminum alloy studied.*

Keywords*. AA7175, mechanical behavior, strain-controlled fatigue, stress-controlled fatigue, mechanical testing.*

1. Introduction

When a metal is loaded, elastic and plastic deformation could happen, and the Ramberg-Osgood relation, showed in Eq. (1), is valid (Dowling, 1999):

$$\varepsilon = \varepsilon_e + \varepsilon_p = \frac{\sigma}{E} + \left(\frac{\sigma}{H}\right)^{1/n} \tag{1}$$

where ε is the total strain resulting from loading, ε_e and ε_p are respectively the elastic and plastic strain resulting from loading, σ is the normal stress applied, E is the modulus of elasticity, H is the strain hardening coefficient and n is the strain hardening exponent of the material.

The mechanical behavior of a metallic material submitted to cyclic loading, however, could differ from the behavior found when it was monotonically loaded. During cyclic loading at constant strain range $\Delta\varepsilon$ (calculated as the difference between maximum and minimum strain at each load cycle) the stress range $\Delta\sigma$ (calculated as the difference between maximum and minimum stress in a cyclic load) generally changes. Some materials exhibit cyclic hardening, which means that the stress range increases during cyclic loading; if the stress range decreases, cyclic softening occurs. However, after cyclic hardening or softening metallic materials develop a stable $\Delta\sigma$ for a given $\Delta\varepsilon$ (Dowling, 1999). This allows Eq. (1) to be re-written, given:

$$\varepsilon_a = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{H'}\right)^{1/n'} \tag{2}$$

where ε_a is the strain amplitude (half of $\Delta\varepsilon$ value) resulting from cyclic loading, σ_a is the stress amplitude (half of $\Delta\sigma$ value), E is the modulus of elasticity, H' is the cyclic strain hardening coefficient and n' is the cyclic strain-hardening exponent of the material.

The cyclic stresses and strains related to cyclic loading of metals produce microscopic physical damage; this could lead to nucleation of microcracks, and subsequent stable crack propagation until final failure. This failure process, very common in metals and alloys, is called fatigue. The first work on fatigue failure is credited to Albert (1838), but the works of Wöhler (1860) and Basquin (1910) were the beginning of stress-controlled fatigue tests (Schütz, 1996). Increasing stress amplitude (s_a) results in decreasing number of cycles to failure (N_f) according to the Basquin relation, modified by Morrow in 1968 (Suresh, 1998):

$$s_a = (s_f' - s_m)(2N_f)^b \tag{3}$$

where s_f' is the fatigue strength coefficient, s_m is the mean stress during loading (which is zero when the ratio between minimum and maximum stresses is –1) and b is the fatigue strength (or Basquin) exponent. Typical values of b are between –0,05 and –0,12, and in many cases s_f' are equal to the true fracture stress in a monotonic load. However, high strength aluminum alloys could have b values near –0,34, and s_f' could reach values three times larger than true fracture stress (Lampman, 1996).

Considering to important factors of fatigue failure: i) metallic materials could present cyclic hardening or softening and ii) the mechanical damage promoted by cyclic loading is related to localized plastic deformation (glide of dislocations), it was found that stress-controlled approach of fatigue life determination neglects the plastic deformation presented at the damage process. Using the concept of total strain amplitude of Eq. 2, the assumption that Eq. (3) describes the elastic contribution of total strain during cyclic loading and the works of Coffin and Mason (1954), it is possible to write the basic relation of strain-controlled fatigue life determination, when the mean stress applied during cyclic loading is zero (Suresh, 1998):

$$e_a = \frac{s_f'}{E}(2N_f)^b + e_f'(2N_f)^c \tag{4}$$

where e_f' is the fatigue ductility coefficient and c is the fatigue ductility (or Coffin) exponent. Typical values of c are between –0,5 and –0,7, and in many cases e_f' are equal to the true fracture strain in a monotonic load. Once again, high strength aluminum alloys could have c values up to –1,2, and e_f' could reach values seven times larger than true fracture strain (Lampman, 1996). ASTM E 606-92 normalizes strain-controlled fatigue tests.

The very unusual values of fatigue variables (b, c, s_f', e_f') found in high strength aluminum alloys (as the AA7xxx series, where zinc is the major alloying element) are the motivation of this work, which describes the mechanical behavior (monotonic and cyclic) of AA7175-T1 aluminum alloy (naturally aged from solution treatment temperature found in hot extrusion), and compares the strain-controlled fatigue tests with the results of previous work (Magnabosco, 2001) regarding stress-controlled fatigue tests of the same material.

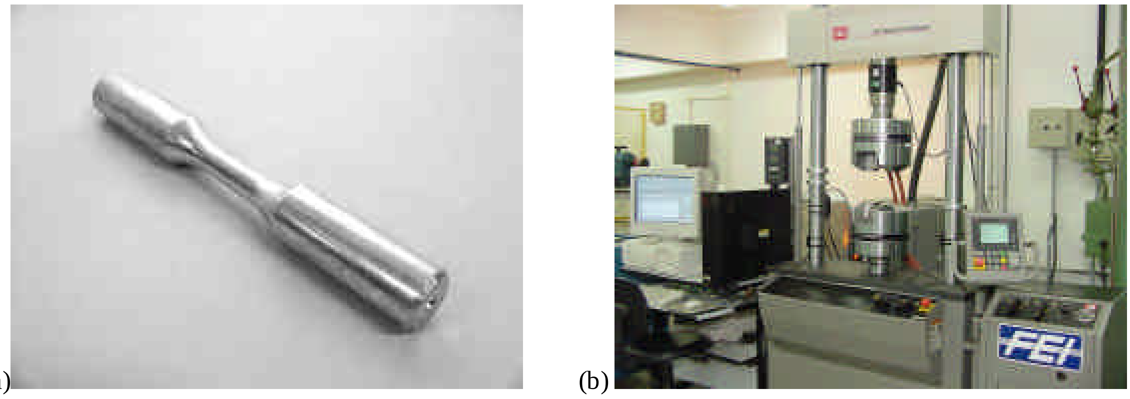
2. Experimental procedure

Test specimens, according to ASTM E 606-92 procedure, were produced from round bars (diameter 20 mm) of AA7175-T1 aluminum alloy, and its chemical composition is shown in Tab. (1). The uniform gage section of the specimens was polished with 2-μm diameter chromium oxide, and Fig. (1.a) shows one specimen ready for mechanical tests.

Table 1. Chemical composition of the studied AA7175-T1 aluminum alloy.

element	Zn	Mg	Cu	Cr	Si	Mn	Al
weight %	5.13	2.32	1.40	0.18	0.09	0.02	balance

The monotonic behavior of the alloy was determined by eight tension tests conducted in a 250 kN MTS universal machine, showed in Fig. (1.b). Strain-controlled tests, using a 25 mm gage length extensometer, were conducted in the same equipment, loading the specimens in strain amplitudes from 0.006 to 0.02. The test frequency was maintained in 0.5 Hz, allowing the test temperature to be 22±2°C. The results were compared to those obtained in a previous work (Magnabosco, 2001), where stress-controlled tests were conducted in specimens without final polishing, with σ_m varying from 185 MPa to 260 MPa, and the ratio (σ_a / σ_m) was maintained between 0.36 and 1, in order to compare the fatigue variables b and s_f' obtained in the strain-controlled tests with those obtained in stress-controlled ones.



(a) (b)

Figure 1. (a) Specimen used in monotonic and cyclic tests. (b) MTS universal machine used, located at LabMat-FEI.

3. Results and discussion

Figure 2 compares the monotonic and cyclic true stress-strain curves found in monotonic and cyclic loading tests, showing that AA7175-T1 alloy exhibits cyclic hardening. An accurate study of monotonic tests leads to the data treatment showed in Fig. (3), where the strain hardening coefficient and exponent of the Ramberg-Osgood relation (Eq. (1)) are, respectively 833 MPa and 0.064. The same treatment was applied to the cyclic results, resulting in values of H' and n' of 783 MPa and 0.038, as showed in Fig. (4).

From the cyclic, strain-controlled, fatigue tests it was possible to draw Fig. (5), showing strain amplitude as a function of the number of cycles to failure. Green dots represent the plastic strain amplitude; purple dots, the elastic strain amplitude and blue dots, the total strain amplitude found in the experimental data. Solid lines are calculated from equations showed in the figure, and it was possible to determine all the fatigue variables of AA7175-T1 aluminum alloy. Table 2 summarizes the mechanical behavior found after monotonic and cyclic (strain-controlled) loading tests. It was found that s_f' and e_f' values for AA7175-T1 alloy cannot be approximated from true fracture stress and strain obtained in monotonic tests.

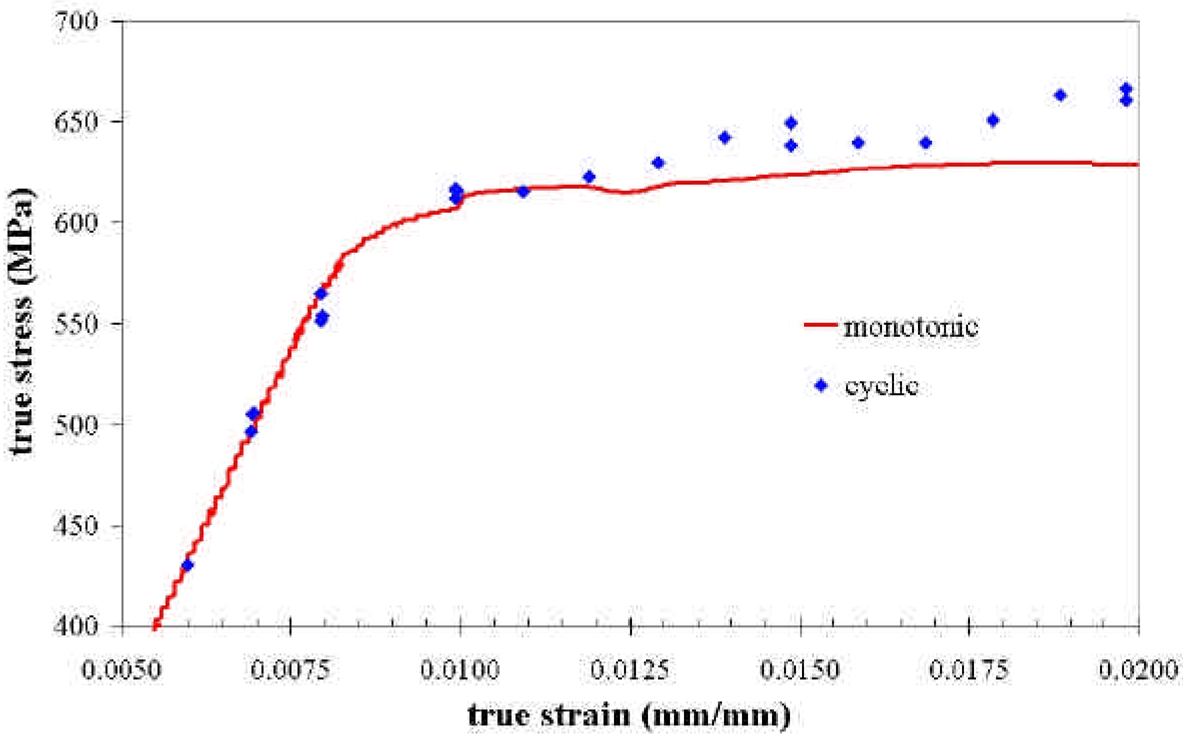


Figure 2. Comparison between monotonic and cyclic true stress-strain typical curves for the AA7175-T1 studied.

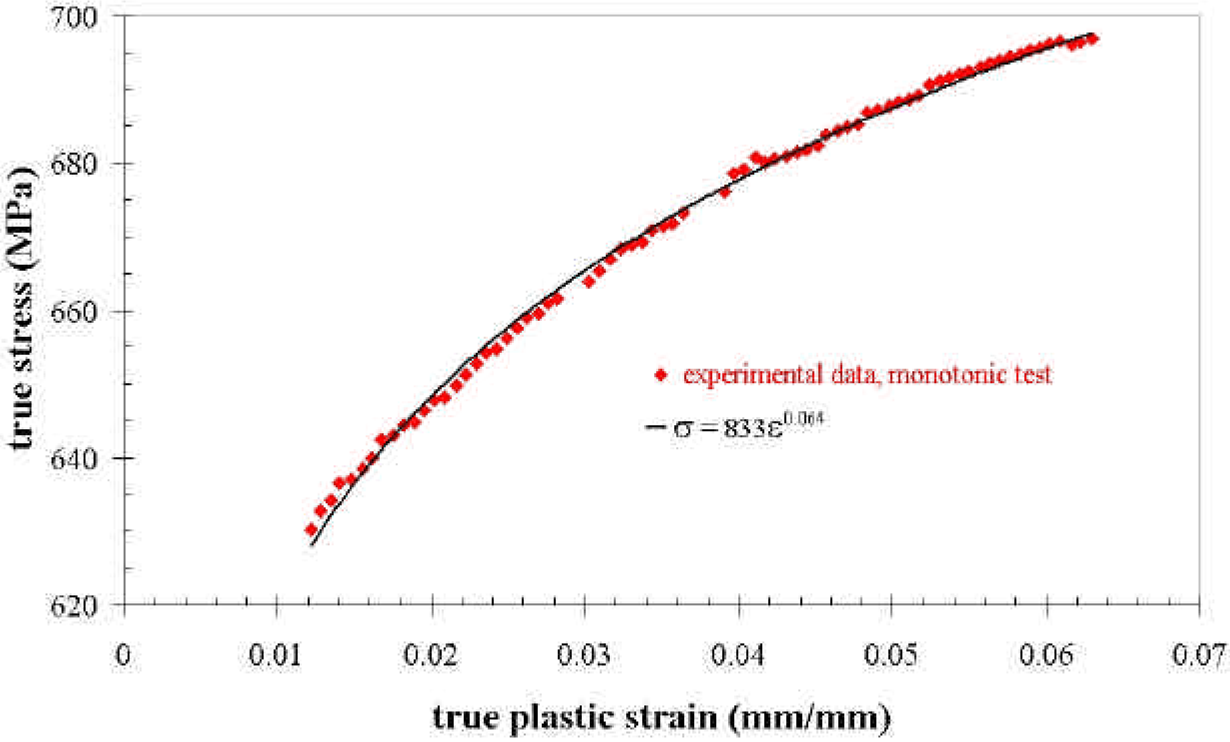


Figure 3. True stress *vs*. true plastic strain found in monotonic tests and the Ramberg-Osgood relation of plastic strain for AA7175-T1 aluminum alloy.

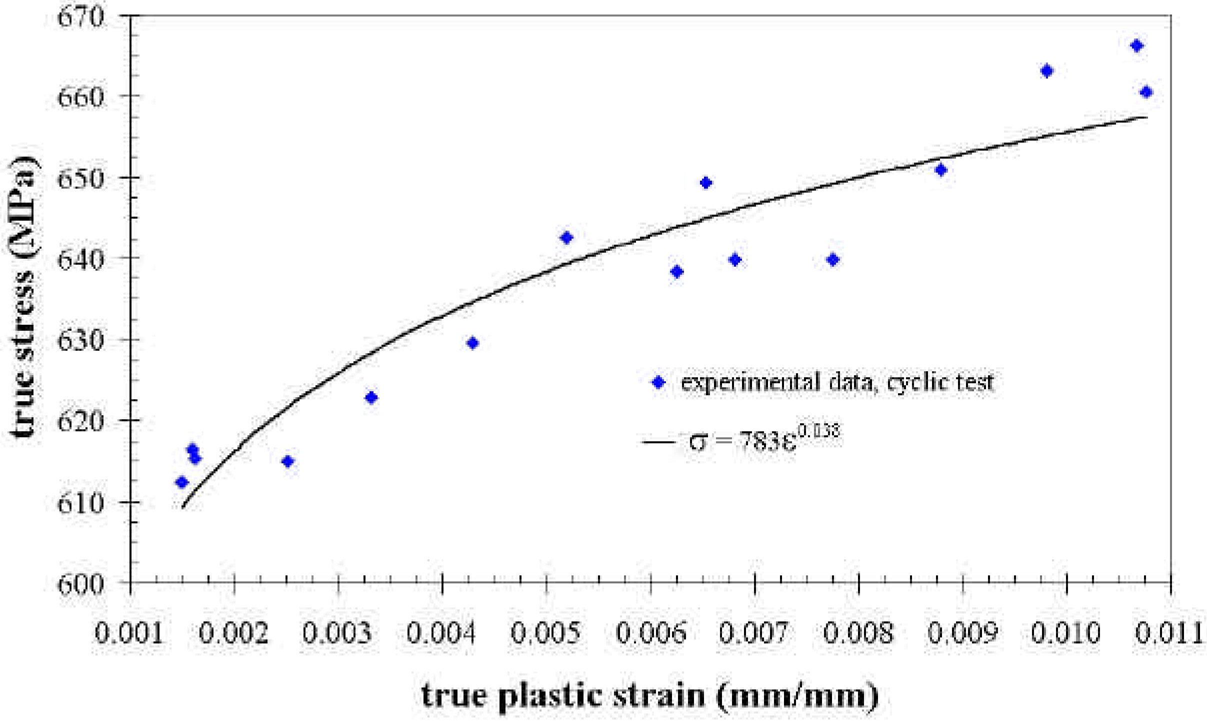


Figure 4. True stress *vs*. true plastic strain found in cyclic tests and the Ramberg-Osgood relation of plastic strain for AA7175-T1 aluminum alloy.

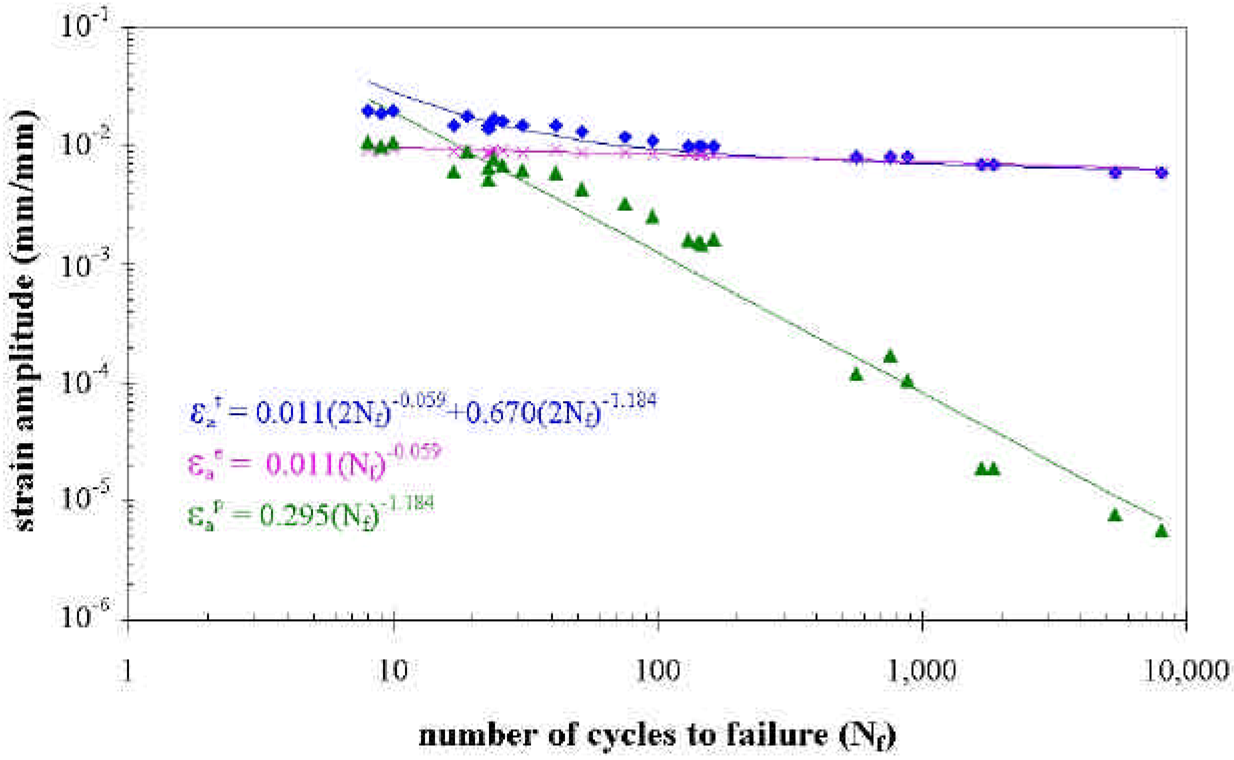


Figure 5. Strain amplitude as a function of the number of cycles to failure for AA7175-T1 aluminum alloy. Green dots represent the plastic strain amplitude; purple dots, the elastic strain amplitude and blue dots, the total strain amplitude found in the experimental data. Solid lines are calculated from equations showed in the figure.

Table 2. Mechanical properties found in monotonic and cyclic (strain-controlled) loading tests of AA7175-T1 aluminum alloy.

Modulus of elasticity, E (GPa)	70.1 ± 1.1
Yield strength (MPa)	609 ± 6.5
Tensile strength (MPa)	651 ± 7.0
True fracture stress (MPa)	719 ± 1.2
Area reduction (%)	11.9 ± 1.4
Total elongation in 25 mm (%)	9.8 ± 1.4
True fracture strain (mm/mm)	0.127 ± 0.014
Strain hardening coefficient, H (MPa)	833
Strain hardening exponent, n	0.064
Cyclic strain hardening coefficient, H' (MPa)	783
Cyclic strain hardening exponent, n'	0.038
Fatigue strength coefficient, σ_f' (MPa)	771
σ_f' / E	0.011
Fatigue strength exponent, b	-0.059
Fatigue ductility coefficient, ε_f'	0.670
Fatigue ductility exponent, c	-1.184

Table 3 shows the mechanical behavior of the studied material compared to various AA7xxx aluminum alloys related in the literature (Endo and Morrow, 1969; ASM, 1997). As could be noticed, cyclic behavior of the AA7xxx aluminum alloys is strongly related to the imposed heat treatment. For example, the fatigue ductility exponent (c) could vary from –1.231 to –0.730, and the fatigue ductility coefficient could reach values up to 10.202. However, considering the unusual heat treatment imposed to the studied material (T1 - naturally aged to a stable condition after hot forming) and the lack in literature about AA7175 aluminum alloy data, it's possible to affirm that mechanical behavior of AA7175-T1 aluminum alloy is well defined in this study.

Table 3. Mechanical behavior comparison between various AA7xxx aluminum alloys and the studied material.

Material	7075-T6[1]	7075-T6[2]	7075-T65[2]	7075-T73[2]	7075-T7351[2]	7475-T761[2]	**AA7175-T1 (this work)**
Modulus of elasticity (GPa)	71	71	72	71	71	-.-.-	**70.1**
Yield strength (MPa)	469	470	-.-.-	413	382	414	**609**
Tensile strength (MPa)	579	580	-.-.-	482	462	475	**651**
True fracture stress (MPa)	800	801	-.-.-	579	-.-.-	-.-.-	**719**
Area reduction (%)	33	33	-.-.-	23	8.4	13.5	**11.9**
True fracture strain (mm/mm)	0.41	-.-.-	-.-.-	0.26	-.-.-	-.-.-	**0.127**
n	0.113	0.113	-.-.-	0.054	-.-.-	-.-.-	**0.064**
H (MPa)	-.-.-	913	646	593	695	-.-.-	**833**
n'	0.11	0.088	0.032	0.032	0.094	0.059	**0.038**
H' (MPa)	-.-.-	913	-.-.-	510	695	675	**783**
s'_f (MPa)	-.-.-	886	1294	800	989	983	**771**
b	-.-.-	-0.076	-0.125	-0.098	-0.140	-0.107	**-0.059**
e_f'	-.-.-	0.446	10.202	-0.260	6.812	4.246	**0.670**
c	-.-.-	-0.759	-1.231	-0.730	-1.198	-1.066	**-1.184**

[1] data from Endo and Morrow (1969); [2] data from ASM Handbook (1997)

The stress related fatigue variables *b* and s_f' obtained in the earlier work of Magnabosco (2001) are very different from the values found in this work, as showed in Tab. (4). The principal reasons for that could be credited to the great difference in surface preparation of the specimens: on the previous work (Magnabosco, 2001), uniform gage section were grounded to #220, while specimens in this work were polished, reducing the stress concentration at specimen's surface. Another important aspect is the influence of plastic strain in the fatigue behavior of this alloy, which was neglected during the stress-controlled tests of the earlier work (Magnabosco, 2001). In fact, the high absolute value of *b* found in the earlier work (Magnabosco, 2001) leaded to the high fatigue strength coefficient (σ_f') found. Considering that σ_f' could be assumed as the stress amplitude when N_f is 0.5, to higher absolute values of b, higher σ_f' values will be found. High absolute values of *b* could be credited to stress-controlled tests near the transition fatigue life zone, where the elastic and plastic components of applied strain are equal, confirming the influence of plastic strain in the fatigue behavior of this alloy. This is an indication that strain-controlled tests are more reliable to determine cyclic behavior of AA7175-T1 aluminum alloy.

Table 4. Comparison of fatigue variables obtained in strain-controlled and stress-controlled fatigue tests.

Variable	Strain-controlled (this work)	Stress-controlled (Magnabosco, 2001)
Fatigue strength coefficient, σ_f' (MPa)	771	7223
Fatigue strength (Basquin) exponent, b	-0.059	-0.335

Considering the time used to reach ten valid experimental points in the two kinds of tests (in according to the minimum pointed by ASTM E 606-92), it was found that strain-controlled fatigue tests needed half of the experimental time expended with stress-controlled tests, regarding the better surface finishing of the specimens and the lower cycle frequency needed in strain-controlled fatigue tests. This, and the fact that more fatigue variables could be found, made the strain-controlled fatigue test a better choice for the understanding of the cyclic mechanical behavior of the AA7175-T1 aluminum alloy.

4. Conclusions

It could be concluded from this work that:

- The AA7175-T1 aluminum alloy monotonic behavior could be described using a Ramberg-Osgood type expression:

$$e = \frac{s}{70100} + \left(\frac{s}{833}\right)^{1/0.064}$$, where MPa is the stress unit.

- The AA7175-T1 aluminum alloy exhibits cyclic hardening when is cyclic loaded, and its Ramberg-Osgood relation in cyclic loading could be described as:

$$e_a = \frac{s_a}{70100} + \left(\frac{s_a}{783}\right)^{1/0.038}$$, where MPa is the stress unit.

- The fatigue life of AA7175-T1 aluminum alloy could be estimated by

$$e_a = 0.011\left(2N_f\right)^{-0.059} + 0.670\left(2N_f\right)^{-1.184}$$

- Fatigue strength and ductility coefficients for AA7175-T1 aluminum alloy cannot be approximated from true fracture stress and strain obtained in monotonic tests.
- When compared to stress-controlled fatigue test, strain-controlled fatigue test is a better choice for characterizing the cyclic mechanical behavior of the AA7175-T1 aluminum alloy, especially on the prediction of fatigue life, as a result of the plastic strain influence on the fatigue behavior of this alloy.

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