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EVALUATION OF METHODS FOR ESTIMATING FATIGUE PROPERTIES APPLIED TO STAINLESS STEELS AND ALUMINUM ALLOYS

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Abstract

This work evaluate seven estimation methods of fatigue properties applied to stainless steels and aluminum alloys. Experimental strain-life curves are compared to the estimations obtained by each method. After applying seven different estimation methods at 14 material conditions, it was found that fatigue life can be estimated with good accuracy only by the Bäumel-Seeger method for the martensitic stainless steel tempered between 300°C and 500°C. The differences between mechanical behavior during monotonic and cyclic loading are probably the reason for the absence of a reliable method for estimation of fatigue behavior from monotonic properties for a group of materials.
Key words: Strain-controlled fatigue; Fatigue lige; Stainless steel; Aluminum alloys.

1 INTRODUCTION

Monotonic mechanical properties can be easily obtained at tension tests, with great accuracy. The most important variables extracted from a monotonic stress--strain curve that characterize the monotonic mechanical behavior are Young's modulus (E), yield strength (Y_S), ultimate tensile strength (T_S), total elongation (TE), area reduction at fracture (AR), true fracture stress (σ_F) and strain (ε_F), strength coefficient (H) and strain-hardening exponent (n) of the Ramberg-Osgood equation (Equation 1):[(1)]

$$\varepsilon = \varepsilon_E + \varepsilon_P = \frac{\sigma}{E} + \left(\frac{\sigma}{H}\right)^{\frac{1}{n}} \quad (1)$$

where ε is the total strain applied during monotonic loading, ε_E is the elastic strain and ε_P is the plastic strain. When a metal is cyclically loaded, a modification of the Ramberg-Osgood is valid:

$$\frac{\Delta\varepsilon_T}{2} = \frac{\Delta\varepsilon_E}{2} + \frac{\Delta\varepsilon_P}{2} = \frac{\Delta\sigma}{2E} + \left(\frac{\Delta\sigma}{2H'}\right)^{\frac{1}{n'}} \quad (2)$$

where $\Delta\varepsilon_T/2$ is the total strain amplitude applied during cyclic loading, $\Delta\varepsilon_E/2$ is the elastic strain amplitude and $\Delta\varepsilon_P/2$ is the plastic strain amplitude. From this equation, the cyclic strength coefficient (H') and cyclic strain-hardening exponent (n') can be defined, allowing the comparison between monotonic and cyclic mechanical behaviors.

Metallic materials present cyclic hardening when the cyclic stress-strain curve described by Equation 2 shows higher stress values in a specific strain level when compared to those predicted by Equation 1. However, cyclic softening or a mixed behavior could also be observed. Hertzberg[(2)] relates the tendency of a given material to undergo cyclic hardening or softening to the quotient T_S/Y_S: if the quotient is higher than 1.4, cyclic hardening was expected, and when the quotient is lower than 1.2, cyclic softening is the most common behavior observed. In the same way, there is a tendency to observe cyclic hardening if the monotonic strain-hardening exponent (n) is higher than 0.2; cyclic softening can be observed if n is lower than 0.1.

During cyclic loading, fatigue failure can occur, and for mechanical design the determination of the fatigue life under an applied load is desired. Strain-controlled fatigue tests can generate strain-life fatigue curves, which can be generally described by:

$$\frac{\Delta\varepsilon_T}{2} = \frac{\Delta\varepsilon_E}{2} + \frac{\Delta\varepsilon_P}{2} = C_E \cdot (N_F)^b + C_P \cdot (N_F)^c \quad (3)$$

where N_F is the number of cycles to failure, the elastic term of the total strain imposed can be described by the elastic coefficient (C_E) and the fatigue strength exponent (b), and the plastic term is described by the plastic coefficient (C_P) and by the fatigue strain exponent (c).[(3)]

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Cyclic and fatigue tests are more time-consuming than monotonic tension tests, leading to great availability of monotonic properties. This naturally leads to the development of methods for the estimation of fatigue properties from monotonic ones.[4] This work analyzes seven estimation methods, described in the following topics.

Four-point method (4P): this method received this name because it uses two points to determine the elastic term of the strain-life curve (in a log-log plot), and other two for the plastic term.[5] Algebraically, it can be described by:

$$\frac{\Delta\varepsilon_T}{2} = C_{E_{(4P)}} \cdot (N_F)^{b_{(4P)}} + C_{P_{(4P)}} \cdot (N_F)^{c_{(4P)}} \quad (4)$$

where:

$$b_{(4P)} = -0.1785 \cdot \log\left[2.78(1+\varepsilon_F)\right] \quad (5)$$

$$M_1 = \frac{T_S}{E} \quad (6)$$

$$M_2 = \log\left[2.5 \cdot M_1(1+\varepsilon_F)\right] \quad (7)$$

$$C_{E_{(4P)}} = \frac{1}{2} \cdot 10^{0.301 \cdot b_{(4P)} + M_2} \cdot 2^{b_{(4P)}} \quad (8)$$

$$M_3 = 10^{4.602 \cdot b_{(4P)} + M_2} \quad (9)$$

$$M_4 = \log\left(0.25 \cdot \varepsilon_F^{0.75}\right) \quad (10)$$

$$c_{(4P)} = 0.333 \cdot \left[\log(0.00691 - 0.52356 \cdot M_3) - M_4\right] \quad (11)$$

$$C_{P_{(4P)}} = \frac{1}{2} \cdot 10^{-1.301 \cdot c_{(4P)} + M_4} \cdot 2^{c_{(4P)}} \quad (12)$$

Universal slopes (US): this method fixed the elastic and plastic slopes, related to the fatigue strength and strain exponents (*b* and *c*) at –0.12 and –0.6, respectively.[6] This leads to:

$$\frac{\Delta\varepsilon_T}{2} = C_{E_{(IU)}} \cdot (N_F)^{-0.12} + C_{P_{(IU)}} \cdot (N_F)^{-0.6} \quad (13)$$

where

$$C_{E_{(IU)}} = 1.75 \cdot M_1 \quad (14)$$

$$C_{P_{(IU)}} = 0.5.\varepsilon_F^{0.6} \quad (15)$$

Mitchell method (Mit): also known as Socie et al method, is developed for steels with hardness below 500 HB.[3] It is assumed that fatigue strength coefficient is numerically equal to the true fracture stress, and the fatigue strain coefficient can be assumed as the total strain at fracture. The fatigue strain exponent is again fixed at –0.6, resulting in:

$$\frac{\Delta\varepsilon_T}{2} = C_{E_{(Mit)}} \cdot (N_F)^{b} + C_{P_{(Mit)}} \cdot (N_F)^{-0.6} \quad (16)$$

where

$$C_{E_{(Mit)}} = M_5 \cdot 2^{b_{(Mit)}} \quad (17)$$

$$M_5 = \frac{\sigma_F}{E} \quad (18)$$

$$b_{(Mit)} = -\frac{1}{6}\log\left(\frac{2 \cdot M_5}{M_1}\right) \quad (19)$$

$$C_{P_{(Mit)}} = 0.66 \cdot \varepsilon_F \quad (20)$$

Bäumel-Seeger method: two different sets of equations are used in this method.[3] For low-alloy and carbon steels, generally called ferrous materials, the main expression (BS_F) is:

$$\frac{\Delta\varepsilon_T}{2} = C_{E_{(BS_F)}} \cdot (N_F)^{-0.087} + C_{P_{(BS_F)}} \cdot (N_F)^{-0.58} \quad (21)$$

where

$$C_{E_{(BS_F)}} = 1.412 \cdot M_1 \quad (22)$$

$$C_{P_{(BS_F)}} = 0.395 \cdot M_6 \quad (23)$$

considering that $M_6 = 1$ if $M_1 \leq 0.003$ and $M_6 = 1.375 - 125 \cdot M_1$ if $M_1 > 0.003$. For non-ferrous alloys (specifically aluminum or titanium alloys), the method (BS_N) is described by:

$$\frac{\Delta\varepsilon_T}{2} = C_{E_{(BS_N)}} \cdot (N_F)^{-0.095} + 0.217 \cdot (N_F)^{-0.69} \quad (24)$$

where

$$C_{E_{(BS_N)}} = 1.564 \cdot M_1 \quad (25)$$

Modified four-point method (4PM): Ong[5] proposes some modifications to the previously discussed four-point method for a better fit to experimental fatigue data of steels. The estimation of the strain-life curve is possible through:

$$\frac{\Delta\varepsilon_T}{2} = C_{E_{(4PM)}} \cdot (N_F)^{b_{(4PM)}} + C_{P_{(4PM)}} \cdot (N_F)^{c_{(4PM)}} \quad (26)$$

where

$$b_{(4PM)} = \frac{1}{6}\left[\log\left(0.16 \cdot M_5^{0.81}\right) - \log(M_5)\right] \quad (27)$$

$$C_{E_{(4PM)}} = M_5 \cdot 2^{b_{(4PM)}} \quad (28)$$

$$M_7 = M_5 \cdot 10^{4 \cdot b_{(4PM)}} \quad (29)$$

$$c_{(4PM)} = \frac{1}{4}\left[\log\left(0.00355 - 0.48216 \cdot M_7\right) - \log(\varepsilon_F)\right] \quad (30)$$

$$C_{P_{(4PM)}} = \varepsilon_F \cdot 2^{c_{(4PM)}} \quad (31)$$

Modified universal slopes method (MUS): some modifications on the previously described US method are proposed,[3] allowing the estimation of the strain-life curve by:

$$\frac{\Delta\varepsilon_T}{2} = C_{E_{(MUS)}} \cdot (N_F)^{-0.09} + C_{P_{(MUS)}} \cdot (N_F)^{-0.56} \quad (32)$$

where

$$C_{E_{(MUS)}} = 0.585 \cdot M_1^{0.832} \quad (33)$$

$$C_{P_{(MUS)}} = 0.0133 \cdot \varepsilon_F^{0.155} \cdot M_1^{-0.53} \quad (34)$$

Morrow[7] also shows that fatigue strength and ductility exponents (b and c) can be estimated from cyclic strain hardening exponent (n'), according to:

$$b = \frac{-n'}{1 + 5n'} \quad (35)$$

$$c = \frac{-1}{1 + 5n'} \quad (36)$$

Re-arranging Equations 35 and 36 lead to:

$$n' = \frac{b}{c} \quad (37)$$

Considering those facts, the main purpose of this work is the evaluation of the estimation methods presented, analyzing their applicability and accuracy in two duplex stainless steels (UNS S31803, also known as 2205, and UNS S32750, also known as 2507), a martensitic stainless steel UNS S42000 (quenched and tempered in seven different conditions, obtaining different strength levels), two cast (A413.0 and A356.0) and three wrought (AA7175-T1, AA6261-T6 and AA6351-T6) aluminum alloys. Experimental strain-life curves are compared to the estimated strain-life curves obtained by each presented method.

2 EXPERIMENTAL

Cast aluminum samples were obtained by low-pressure die casting, and the wrought aluminum alloys and stainless steels were obtained from commercial round bars of approximately 20 mm diameter. Tables 1 and 2

Table 1. Chemical composition (wt%) of the studied aluminum alloys, and identification (ID) used

Material	Mg	Mn	Si	Fe	Zn	Cu	Cr	Ti	Al	ID
A413.0	0.08	-	10.94	0.17	-	-	-	0.120	balance	A413
A356.0	0.32	-	7.44	0.14	-	-	-	0.130		A356
AA7175-T1	2.32	0.02	0.09	-	5.13	1.400	0.180	-		7175
AA6261-T6	0.68	0.26	0.31	0.33	0.03	0.130	0.002	0.007		6261
AA6351-T6	0.59	0.43	0.44	0.28	0.02	0.006	0.001	0.006		6351

Table 2. Chemical composition (wt%) of the studied stainless steels, and identification (ID) used

Material	C	Cr	Si	Ni	Mn	Mo	N	Fe	ID
UNS S42000	0.380	12.28	0.45	0.14	0.52	-	-	balance	MXXX*
UNS S31803	0.015	22.20	0.50	5.40	0.80	3.2	0.18		2205
UNS S32750	0.015	25.00	0.30	6.90	0.40	3.8	0.26		2507

*MXXX indicates tempering temperature in °C for martensitic stainless steels.

show the chemical composition (wt%) of the studied materials. While duplex stainless steels presents only solution-treated structures, martensitic stainless steels were oil quenched from 1000°C and then tempered for 1 hour at 200°C, 300°C, 400°C, 450°C, 500°C, 550°C or 600°C, to obtain different strength levels. Wrought aluminum alloys are solution-treated and naturally aged (AA7175-T1 alloy) or artificially aged (AA6261-T6 and AA6351-T6 alloys).

Tension tests following ASTM E8M[8] were conducted in a servo-hydraulic MTS 810.25 testing machine. For each material were determined: Young's modulus (E), yield strength (Y_S), ultimate tensile strength (T_S), total elongation in 25 mm (TE^{25}), reduction of area (RA), true fracture stress (σ_F), true fracture strain (ε_F), strength coefficient (H) and strain-hardening exponent (n). In the same testing machine, strain-controlled fatigue tests were conducted according to ASTM E606,[9] with a maximum test frequency of 0.5 Hz to avoid heating of the specimens during cyclic loading, and strain ratio R = –1, with application of load with sinusoidal wave. From the cyclic tests, the following properties are determined: fatigue strength (b) and ductility (c) exponents, elastic (C_E) and plastic (C_P) coefficients, cyclic strength coefficient (H') and cyclic strain-hardening exponent (n').

3 RESULTS

Tables 3 and 4 summarize the monotonic mechanical properties extracted from tension tests. Fatigue properties are shown in Table 5. Using Equation 1 and 2 and the data of Tables 4 and 5, the true stress-strain curves for both monotonic and cyclic loadings are plotted, and Figure 1 shows typical behavior of selected materials. All of the aluminum alloys present cyclic hardening

Table 3. Monotonic mechanical properties of the studied materials

Material	E [GPa]	Y_S [MPa]	T_S [MPa]	AR [%]	TE^{25} [%]
A413	65 ± 1	73 ± 16	169 ± 21	15.0 ± 5.5	11.8 ± 3.1
A356	70 ± 2	220 ± 20	292 ± 16	11.8 ± 1.2	10.8 ± 2.0
7175	71 ± 2	611 ± 6	656 ± 10	13.2 ± 2.5	10.0 ± 1.3
6261	69 ± 1	278 ± 10	305 ± 4	61.0 ± 1.7	25.7 ± 1.8
6351	68 ± 3	331 ± 15	355 ± 10	50.4 ± 0.8	20.4 ± 3.1
2205	179 ± 6	532 ± 10	767 ± 8	84.1 ± 1.2	58.5 ± 2.8
2507	198 ± 1	613 ± 3	862 ± 3	75.4 ± 1.1	55.6 ± 1.5
M200	205 ± 1	1576 ± 10	2107 ± 120	3.0 ± 0.7	2.2 ± 0.9
M300	212 ± 2	1509 ± 130	1860 ± 19	32.6 ± 1.8	16.9 ± 2.5
M400	214 ± 2	1394 ± 10	1760 ± 12	29.6 ± 7.4	16.7 ± 1.6
M450	206 ± 13	1435 ± 9	1781 ± 16	32.7 ± 7.2	16.6 ± 2.0
M500	209 ± 3	1380 ± 49	1757 ± 17	21.4 ± 4.6	13.3 ± 2.7
M550	208 ± 3	1286 ± 30	1672 ± 30	13.9 ± 3.9	7.0 ± 1.8
M600	213 ± 3	933 ± 7	1125 ± 10	47.1 ± 0.4	23.0 ± 0.1

Table 4. True stress-strain monotonic mechanical properties of the studied materials

Material	σ_F [MPa]	ε_F	H [MPa]	n
A413	178 ± 16	0.162 ± 0.056	373 ± 46	0.247 ± 0.017
A356	325 ± 18	0.125 ± 0.012	351 ± 37	0.088 ± 0.007
7175	718 ± 8	0.142 ± 0.025	869 ± 3	0.070 ± 0.002
6261	402 ± 7	1.890 ± 0.090	252 ± 12	0.025 ± 0.006
6351	408*	1.400*	297*	0.022*
2205	1943 ± 60	1.840 ± 0.010	748 ± 12	0.056 ± 0.001
2507	1633 ± 67	1.400 ± 0.010	888 ± 5	0.062 ± 0.001
M200	2160 ± 135	0.030 ± 0.007	4299 ± 370	0.160 ± 0.133
M300	1977 ± 65	0.394 ± 0.026	2252 ± 75	0.069 ± 0.003
M400	2015 ± 92	0.354 ± 0.101	2072 ± 27	0.062 ± 0.001
M450	2000 ± 49	0.399 ± 0.107	2142 ± 148	0.064 ± 0.140
M500	2048 ± 79	0.241 ± 0.058	2546 ± 60	0.094 ± 0.008
M550	1767 ± 60	0.150 ± 0.046	3037 ± 147	0.136 ± 0.077
M600	1398 ± 37	0.636 ± 0.006	1452 ± 59	0.069 ± 0.007

*results from only one valid tension test.

(Figures 1a, b), in agreement to Mitchell[10] results for wrought aluminum alloys; however, it is reported[11] a mixed behavior for the AA6061-T651 wrought aluminum alloy, indicating the difficult to determine a generalized behavior based on material type. The two duplex stainless steels present cyclic softening (Figure 1c shows the behavior of UNS S32750); martensitic stainless steels tempered at 200°C and 300°C present cyclic hardening; the other tempered samples show mixed behavior (as shown in Figure 1d).

4 DISCUSSION

The use of Morrow Equations 35 to 37 to estimate b, c and n' values leads to the data presented in Table 6. Those values can be compared to the experimental determined ones, presented in Table 5, using the relation:

$$\frac{\Delta X}{X} = \frac{\left| X_{EXP} - X_{Morrow} \right|}{X_{EXP}} \times 100 \tag{38}$$

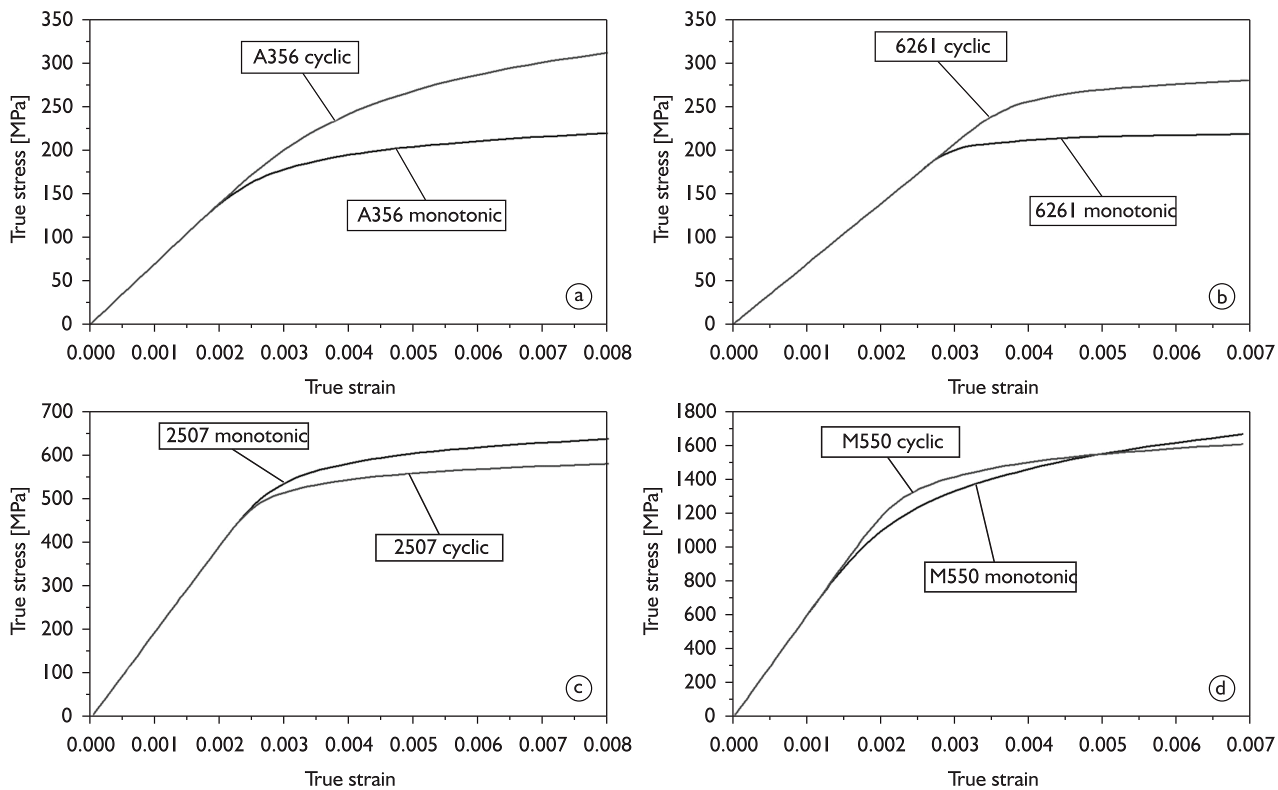

Figure 1. Monotonic and cyclic stress-strain curves for: a) A356.0; b) AA6261-T6; c) UNS S32750; and d) martensitic stainless steels tempered at 550°C.

Table 5. Cyclic mechanical properties of the studied materials

Material	C_E	b	C_P	c	H' [MPa]	n'
A413	0.002	–0.057	2.633	–0.887	128	0.028
A356	0.009	–0.137	0.042	–0.723	676	0.137
7175	0.011	–0.059	0.295	–1.184	783	0.038
6261	0.021	–0.200	2.834	–1.070	353	0.040
6351	0.013	–0.130	2.676	–1.160	456	0.050
2205	0.005	–0.057	0.182	–0.478	733	0.060
2507	0.006	–0.068	0.358	–0.567	743	0.047
M200	0.017	–0.134	0.023	–0.880	4313	0.101
M300	0.012	–0.082	0.530	–0.867	2362	0.067
M400	0.013	–0.090	0.460	–0.818	2375	0.086
M450	0.013	–0.090	0.247	–0.736	2377	0.079
M500	0.013	–0.094	0.304	–0.854	2094	0.053
M550	0.011	–0.074	0.164	–0.714	2157	0.067
M600	0.014	–0.195	0.143	–0.491	4930	0.354

where X_{EXP} are the experimental value of b, c or n' for a given material, and X_{Morrow} is the estimated value. As showed in Table 6, only three predictions of the c values present variations below 10%, and the worst case shows a 367% difference of the estimated value of n' and the experimental result (AA6261 aluminum alloy). Those data shows that Morrow relations (Equations 35 to 37) are not able to predict the desired fatigue properties for the studied materials.

According to Hertzberg,[2] if the quotient $(T_S/Y_S) > 1.4$, cyclic hardening was expected, and when $(T_S/Y_S) < 1.2$, cyclic softening is the most common behavior observed. In the same way, there is a tendency to observe cyclic hardening if the monotonic strain-hardening exponent (n) is higher than 0.2; cyclic softening can be observed if n is lower than 0.1. Using data from Tables 3 and 4 the predictions showed in Table 7 can be stated, showing that only A413.0 aluminum alloy and martensitic stainless steel tempered at 550°C could have their behavior accurately predicted (cyclic hardening and mixed, respectively). It can be concluded that the tendency of cyclic hardening or softening cannot be predicted from monotonic parameters.

Experimental strain-life curves and the seven estimated strain-life curves are shown in Figures 2 to 4 for the wrought aluminum alloy AA7175-T1, the cast aluminum alloy A356.0, duplex stainless steel UNS S31803 and martensitic stainless steel UNS S42000 tempered at 600°C and 400°C, respectively. Those five examples are chosen between the 14 materials studied to illustrate the most usual behaviors observed.

All the estimation methods leads to strain-life curves higher than experimental results of AA7175-T1, as can be seen in Figure 2a, for a fatigue life up to 10^4 cycles; for longer fatigue lifes, sub-estimation occurs. This behavior is also observed for the martensitic stainless steel tempered at 300°C or 550°C.

Table 6. Estimated values of b, c and n', and their variation to experimental values

Material	b_{Morrow}	$\Delta b/b$ [%]	c_{Morrow}	$\Delta c/c$ [%]	n'_{Morrow}	$\Delta n'/n'$ [%]
A413	–0.025	57	–0.877	1	0.064	130
A356	–0.081	41	–0.593	18	0.189	38
7175	–0.032	46	–0.840	29	0.050	31
6261	–0.033	83	–0.833	22	0.187	367
6351	–0.040	69	–0.800	31	0.112	124
2205	–0.046	19	–0.769	61	0.119	99
2507	–0.038	44	–0.810	43	0.120	155
M200	–0.067	50	–0.664	25	0.153	51
M300	–0.050	39	–0.748	14	0.095	41
M400	–0.061	33	–0.697	15	0.111	27
M450	–0.057	37	–0.716	3	0.123	55
M500	–0.042	55	–0.788	8	0.110	105
M550	–0.051	32	–0.747	5	0.104	54
M600	–0.128	34	–0.361	27	0.397	12

Table 7. Observed cyclic hardening or softening behavior and its predictions

Material	Experimental behavior	(T_S/Y_S) prediction		n prediction	
		T_S/Y_S	prediction	n	prediction
A413	hardening	2.32	hardening	0.247	hardening
A356	hardening	1.33	mixed	0.088	softening
7175	hardening	1.07	softening	0.070	softening
6261	hardening	1.09	softening	0.025	softening
6351	hardening	1.07	softening	0.022	softening
2205	softening	1.44	hardening	0.056	softening
2507	softening	1.41	hardening	0.062	softening
M200	hardening	1.33	mixed	0.160	mixed
M300	hardening	1.23	mixed	0.069	softening
M400	mixed	1.26	mixed	0.062	softening
M450	mixed	1.24	mixed	0.064	softening
M500	mixed	1.27	mixed	0.094	softening
M550	mixed	1.30	mixed	0.136	mixed
M600	mixed	1.21	mixed	0.069	softening

However, the estimations for A356.0 cast aluminum alloy (Figure 2b) present longer lifes than experimental results at any load level; this also occurs for the wrought aluminum alloys AA6261-T6 and AA6351-T6 and for the martensitic stainless steel tempered at 200°C. Duplex stainless steels, on the other hand, have shorter estimated fatigue lifes if they are compared to experimental results; Figure 3a illustrates this behavior for UNS S31803 duplex stainless steel.

The modified four-point method (4PM) presents the worst estimation for cast aluminum alloy A413.0 and martensitic stainless steel tempered at 600°C (Figure 3b). For those two materials, BS_N and MUS methods leads to strain-life curves higher than experimental results for a fatigue life up to 10^4 cycles, and for longer fatigue lifes, sub-estimation of fatigue strength occurs some methods leads to lifes than experimental results at any load level; the other methods super-estimate fatigue life.

A simple statistical evaluation, like the correlation coefficients (R^2) between experimental data and estimated values, presents satisfactory results; if all materials are considered, with strain-life curves estimated in a life range from 10^2 to 10^7 by the seven studied methods, the mean correlation factor of all analysis is ($R^2 = 0.98 \pm 0.02$). The lowest correlation factors occur for the 4P ($R^2 = 0.79$) and 4PM ($R^2 = 0.87$) methods applied to the cast aluminum alloy A413.0, and for the 4PM method applied to the AA7175-T1 wrought aluminum alloy ($R^2 = 0.85$). However, the correlation factors does not show with accuracy the poor fit between experimental and estimated strain-life curves illustrated at FigureS 2 and 3. Despite those general observations, UNS S42000 tempered at 300°C, 400°C, 450°C (Figure 4) or 500°C can be estimated by Bäumel--Seeger method with good accuracy.

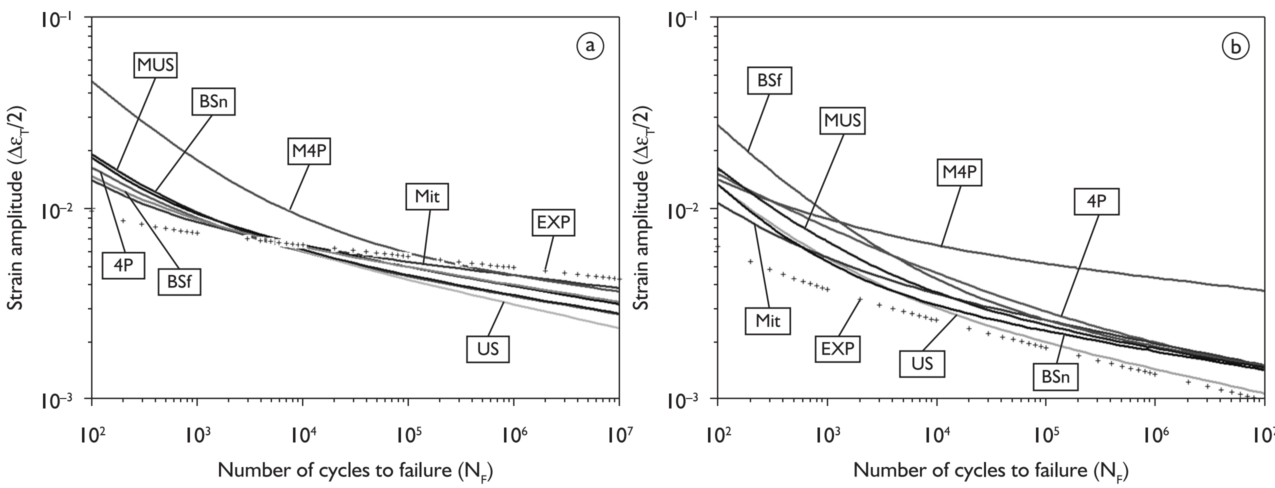

Figure 2. Experimental and estimated strain-life curves for: a) wrought aluminum alloy AA7175-T1 and b) cast aluminum alloy A356.0.

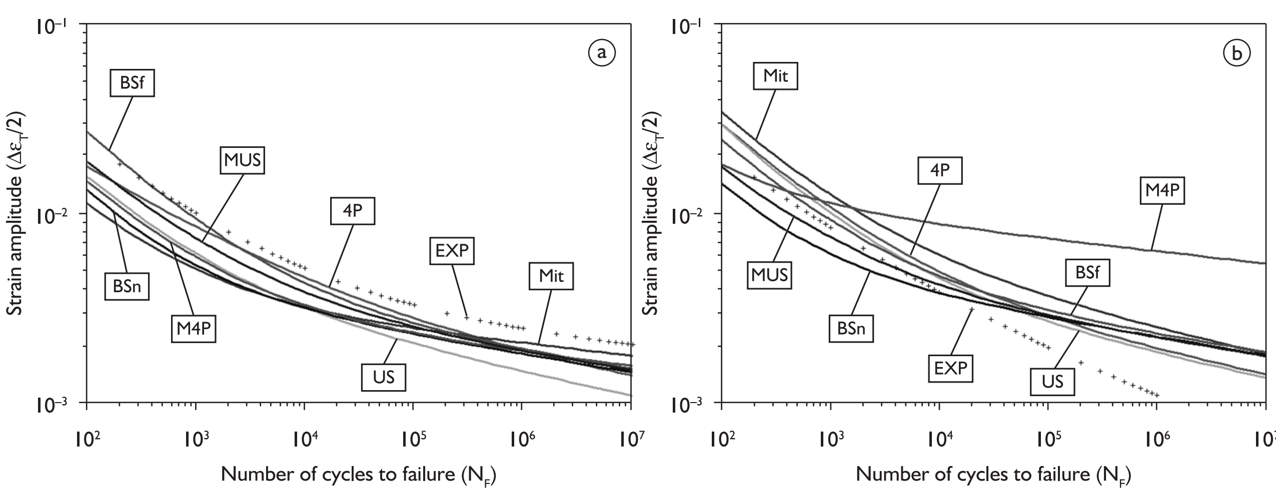

Figure 3. Experimental and estimated strain-life curves for: a) duplex stainless steel UNS S31803 and b) martensitic stainless steel UNS S42000 tempered at 600°C.

Equation 39 allows the determination of a strain amplitude variation (SAV), by the comparison of experimental strain amplitude for a given fatigue life ($\Delta\varepsilon_{EXP}$) and the estimated (or calculated) strain amplitude for a given fatigue life ($\Delta\varepsilon_{CALC}$). Figures 5 and 6 show SAV of the seven estimation methods for wrought aluminum alloy AA6351-T6, cast aluminum alloy A413.0, and martensitic stainless steel UNS S42000 tempered at 200°C or 450°C:

$$SAV = \frac{\Delta\varepsilon_{EXP} - \Delta\varepsilon_{CALC}}{\Delta\varepsilon_{EXP}} \cdot 100 \tag{39}$$

For the wrought aluminum alloy AA6351-T6 (Figure 5a), BS_F and MUS methods show the lowest and most stable SAV (approximately 10%, in a conservative analysis). However, the observed variations does not present the same SAV, for any method, in all the analyzed fatigue life (10^4 to 10^7 cycles); the estimation of fatigue life, in this sense, will depend on the material, desired fatigue life and chosen method, which do not characterizing an accurate estimation of fatigue parameters.

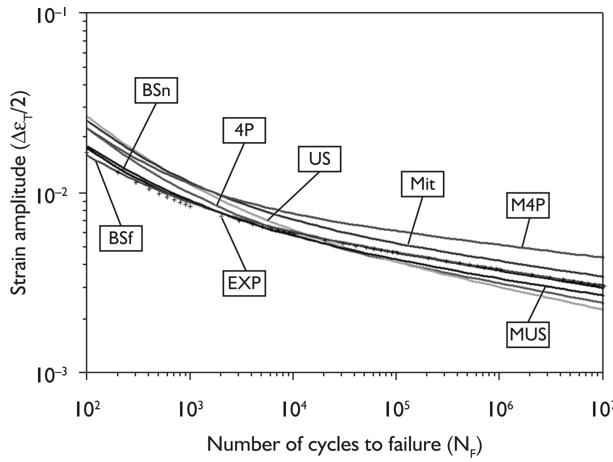

Figure 4. Experimental and estimated strain-life curves for martensitic stainless steel UNS S42000 tempered at 450°C.

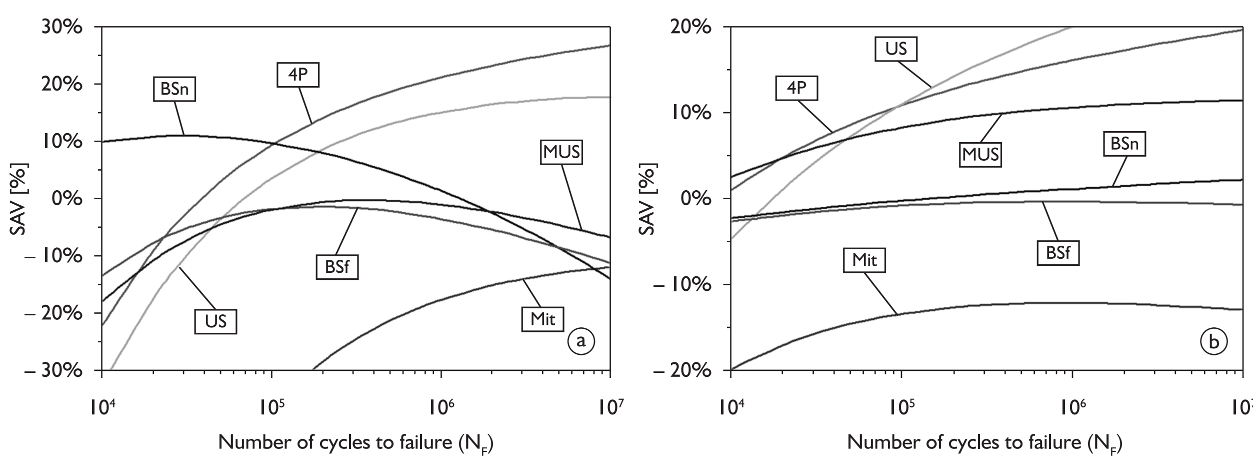

Figure 5. Strain amplitude variation (SAV) between experimental and estimated strain amplitude at specific fatigue lifes for: a) wrought aluminum alloy AA6351-T6 and b) martensitic stainless steel UNS S42000 tempered at 450°C.

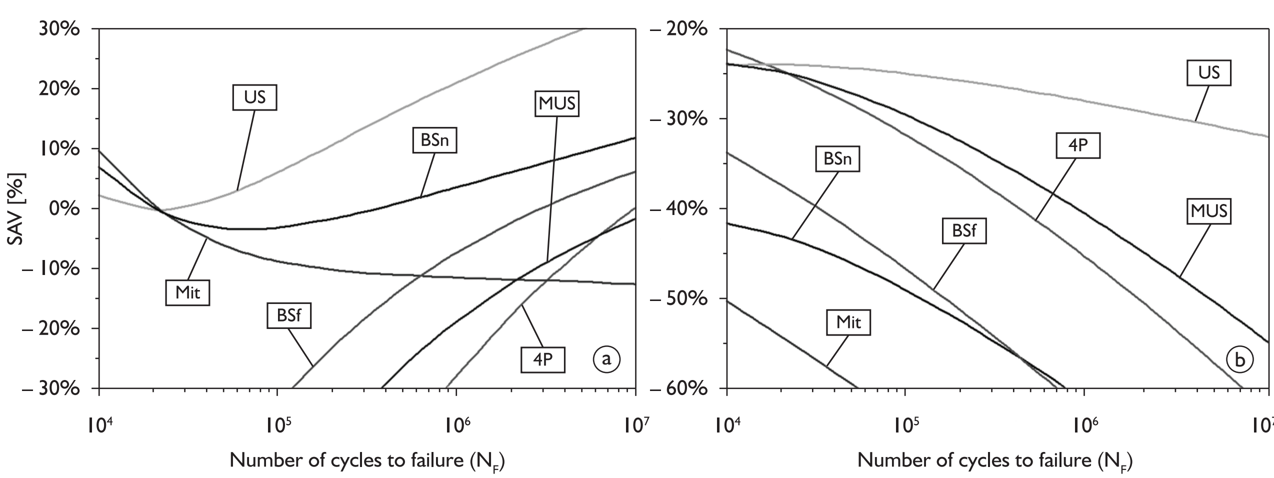

Figure 6. Strain amplitude variation (SAV) between experimental and estimated strain amplitude at specific fatigue lifes for: a) cast aluminum alloy A413.0 and b) martensitic stainless steel UNS S42000 tempered at 200°C.

Figure 5b, however, shows that strain amplitudes for the martensitic stainless steel UNS S42000 tempered at 450°C estimated by BS_N and BS_F methods present stable SAV values, below 3%. Equivalent results are obtained for the same methods for the UNS S42000 tempered between 300°C and 500°C. Nevertheless, the same steel tempered at 200°C (Figure 6b) and 600°C presents large deviations from experimental results, considering all the estimation methods, showing that there is not a secure option to estimate fatigue parameters for this steel.

The lack of a stable SAV for a specific material-method combination is clearly noted in Figure 6a for the cast aluminum alloy A413.0, and the same behavior could be noted for the wrought aluminum alloy AA6261-T6 and for the duplex stainless steels UNS S31803 and UNS S32750. Analyzing all those facts, it can be concluded that none of the evaluated estimation methods can describe the fatigue behavior of a material group. However, UNS S42000 tempered at 300°C, 400°C, 450°C (Figure 5b) or 500°C can be estimated by Bäumel-Seeger method with good accuracy, confirming what is shown by Figure 4.

Table 7 and Figure1 show that the monotonic and cyclic mechanical behaviors are not equivalent, and this is the most probable reason for the absence of a reliable estimation method of fatigue behavior from monotonic properties. The microstrutural changes imposed during cyclic loading deformation, which will lead to the fatigue failure, does not find an equivalent in the monotonic deformation imposed at tension tests, and this could restrain the use of methods for estimation of fatigue behavior from monotonic properties in a more generalized case.

5 CONCLUSIONS

After applying seven different estimation methods at 14 material conditions, this work shows that strain amplitude at a given fatigue life can be estimated with good accuracy only by the Bäumel-Seeger method for the martensitic stainless steel UNS S42000 tempered at 300°C, 400°C, 450°C or 500°C. The differences between mechanical behavior during monotonic and cyclic loading are probably the reason for the absence of a reliable method for estimation of fatigue behavior from monotonic properties for a group of materials.

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LIST OF SYMBOLS

$\Delta\varepsilon_E/2$ – Elastic strain amplitude
$\Delta\varepsilon_P/2$ – Plastic strain amplitude
$\Delta\varepsilon_T/2$ – Total strain amplitude applied during cyclic loading
ε – Total strain applied during monotonic loading
ε_E – Elastic strain
ε_P – Plastic strain
ε_F – True fracture strain
4P – Four-point method
4PM – Modified four-point method
AR – Area reduction at fracture
b – Fatigue strength exponent
BS_F –Bäumel-Seeger method for ferrous materials
BS_N –Bäumel-Seeger method for non-ferrous alloys
c – Fatigue strain exponent
C_E – Elastic coefficient
C_P – Plastic coefficient
E – Young's modulus
H – Strength coefficient of the Ramberg-Osgood equation
H' – Cyclic strength coefficient
Mit – Mitchell method
MUS – Modified universal slopes method
n – Strain-hardening exponent of the Ramberg-Osgood equation
n' – Cyclic strain-hardening exponent
N_F – Number of cycles to failure
SAV – Strain amplitude variation
σ – Stress applied during monotonic loading
σ_F – True fracture stress
TE – Total elongation
TE^{25} – Total elongation in 25 mm
T_S – Ultimate tensile strength
US – Universal slopes method
Y_S – Yield strength