Strain-life Behavior of Different Groups of Metallic Materials

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ABSTRACT. *In proposed paper, strain-life behavior i.e.* $\Delta\varepsilon/2$ - $2N_\mathrm{f}$ *relationships of main groups of metallic materials (non-alloy steels, low alloy steels, high alloy steels, aluminum and titanium alloys) were analyzed across low-cycle, medium-cycle and high-cycle fatigue range. Substantial differences were found to exist among strain-life behaviors of materials belonging to different material groups. This turned out to be in contrast with the fact that most of the existing methods for the estimation of strain-life fatigue parameters from monotonic properties use few expressions and show limited regard as to which group material in question belongs to. It can be concluded that differential approach is required and should be used in developing expressions for estimation of strain-life fatigue parameters. It is expected that individual expressions developed in such a manner will result in more accurate fatigue parameter estimations and hence, more accurate calculations of time to crack initiation both in uniaxial and multiaxial fatigue conditions.*

INTRODUCTION

According to the strain-life approach, the fatigue durability of most metallic materials can be well described by appropriate $\Delta\varepsilon/2$ - $2N_\mathrm{f}$ relationship i.e. Basquin-Coffin-Manson expression:

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\varepsilon_\mathrm{e}}{2} + \frac{\Delta\varepsilon_\mathrm{p}}{2} = \frac{\sigma_\mathrm{f}'}{E}\left(2N_\mathrm{f}\right)^b + \varepsilon_\mathrm{f}'\left(2N_\mathrm{f}\right)^c \quad (1)$$

where σ_f' is fatigue strength coefficient, b is fatigue strength exponent, ε_f' is fatigue ductility coefficient, c is fatigue ductility exponent, E is Youngs modulus and $\Delta\varepsilon$, $\Delta\varepsilon_\mathrm{e}$, and $\Delta\varepsilon_\mathrm{p}$ are total, elastic and plastic strain ranges, respectively. Although Eq. 1 is best suited for calculation of cycles to crack initiation in low-cycle fatigue regime, it can be succesfully applied for the same purpose in case of high-cycle fatigue as well [1].

For determination of fatigue parameters σ_f', b, ε_f' and c, standardized test specimens are submitted to cyclic uniaxial loading in conditions of strain-control [2]. This presents significant deviation from multiaxial and non-proportional state of stress and strain which are present in material of dynamically loaded realistic engineering components during operation. In order to account for this and to improve calculations accuracy of number of load reversals $2N_f$ to crack initiation in conditions which involve presence of multiaxial and non-proportional state of stress and strain, significant number of additions, extensions and changes to Basquin-Coffin-Manson expression were proposed in literature [3, 4, 5]. However, it must be noted that in most of these new crack initiation criteria, basic axial fatigue parameters σ_f', b, ε_f' and c (or their torsional versions τ_f', b_0, γ_f' and c_0) are still required.

Experiment-based determination of Basquin-Coffin-Manson fatigue parameters, although most accurate, is quite prohibitive due to high costs of cyclic experiments and hence, cannot be implemented in early stages of product design when numerous materials/solutions are still being considered. Since monotonic experiments are simple and inexpensive, one of the methods for estimation of fatigue parameters from readily available monotonic material properties is usually implemented in these circumstances. Enhancing accuracy of these estimation methods could contribute to product improvement already at the beginning of its development.

EXISTING METHODS FOR ESTIMATION OF FATIGUE PARAMETERS

Over the years, number of methods for estimation of Basquin-Coffin-Manson fatigue parameters from various monotonic properties was proposed. Most prominent ones along with their characteristics are briefly mentioned here.

In Universal slopes method [6] Manson proposed σ_f' to be estimated from ultimate strength R_m, ε_f' from true fracture ductility ε_f, while to both exponents b and c constant values were assigned. Same author in his Four-point correlation method [6] proposed more intricate expressions which are based on estimates of elastic $\Delta\varepsilon_e/2$ i.e. plastic strain amplitudes $\Delta\varepsilon_p/2$ at four different numbers of loading cycles (N = 1/4, 10, 10^4, 10^5). According to Mitchell's method for steels [7], both σ_f' and b can be estimated from R_m while ε_f presents the basis for calculation of ε_f'. Exponent c is to be assigned constant values, albeit different ones (-0,6 for ductile and -0,5 for strong materials). In 1988 Muralidharan and Manson [8] proposed somewhat modified universal slopes method in which σ_f' is estimated from newly introduced parameter R_m/E, ε_f' from R_m/E and ε_f while constant values of b and c were changed to -0,09 and -0,56, respectively. In their work [9], Bäumel-Seeger were first to consider steels separately from aluminum and titanium alloys. Coefficient σ_f' was related to ultimate strength R_m for both cases. Value of ε_f' depended on value of parameter R_m/E for steels, while for Al and Ti alloys it was assigned constant value 0,35. Exponents were given different constant values for all alloy groups. In his Modified four-point correlation method, Ong [10] made certain modifications to the original method. In [11], Roessle and Fatemi proposed both coefficients σ_f' and ε_f' to be functions of Brinell hardness HB alone, and HB and E respectively. Exponents b and c were assigned identical values as in Modified universal slopes method. In their Medians method Meggiolaro and Castro [12] approached the estimation problem selectively, thus proposing different (although in case of ε_f', b, and c, constant) values for fatigue parameters of steel and aluminum alloys.

Overview of key parameters and/or constant values based on which Basquin-Coffin-Manson fatigue parameters are estimated is given in Table 1.

Table 1. Overview of main estimation methods and their key parameters

Estimation method	σ_f'	b	ε_f'	c
Original universal slopes method (1965) - All materials	R_m	-0,12	ε_f	-0,6
Four-point correlation method (1965) - All materials	b, E, R_m, ε_f	ε_f	c, ε_f	b, E, R_m, ε_f
Method by Mitchell (1977) - Steels	R_m	R_m	ε_f	-0,5 (-0,6)
Modified universal slopes method (1988) - All materials	E, R_m	-0,09	E, R_m, ε_f	-0,56
Uniform material law (1990) - Unalloyed and low-alloy steels	R_m	-0,087	E, R_m	-0,58
Uniform material law (1990) - Al and Ti alloys	R_m	-0,095	E, R_m	-0,69
Modified four-point correlation method (1993) - All materials	R_m, ε_f	E, R_m	ε_f	E, R_m, ε_f, σ_f
Hardness method (2000) - Steels	HB (R_m)	-0,09	E, HB	-0,56
Medians method (2004) - Steels	R_m	-0,09	0,45	-0,59
Medians method (2004) - Al alloys	R_m	-0,11	0,28	-0,66

As it can be seen from above, there are a couple of common points to almost all proposed methods. One of them is establishing direct correlation between chosen monotonic property (or properties) and fatigue parameters (usually coefficients σ_f' and ε_f'). Second one is assigning constant values to fatigue parameters (usually exponents b and c), mostly due to the lack of satisfactory correlation among them and investigated monotonic properties. The third one is (with exception of Uniform material law [9] and Medians method [12]), disregard of the differences in strain-life behavior which certain material groups exhibit (especially those within steel materials).

ANALYSIS OF FATIGUE PARAMETERS AND STRAIN-LIFE DATA

In order to determine existence of potential differences in strain-life behavior of materials belonging to different groups, necessary data was gathered for large number of materials from available literature [9, 11-19]. Data for materials which were tested at less than 4 different strain amplitudes or whose range of strain amplitudes was less than 0,4 % were omitted from analysis. Although in [12] it is suggested that testing temperature does not influence strain-life curves significantly, data obtained with test at elevated temperatures or in cryogenic conditions were excluded as well so that only materials tested at room temperature were taken into account. No such filtering procedure is reported in previous works [7-12]. After filtering, data for total of 310 materials remained for analysis from which 128 belonged to unalloyed steel group (UA), 64 were low-alloy steels (LA), 75 high alloy steels (HA), 30 are aluminum alloys (Al) and 13 titanium alloys (Ti).

Beside hardness, ultimate strength R_m is most readily available monotonic property of the material, and materials are often graded/compared according to it. It also appears as monotonic property from which fatigue parameters are estimated in most cases (Table 1). Since of all monotonic properties, only ultimate strength R_m was known for all considered materials, it was taken as reference parameter according to which individual materials were sorted and their strain-life behavior compared. Ultimate strengths of steel materials under consideration had values within quite a wide range, for unalloyed steels it was from 345 to 2360 MPa, low alloy steels between 435 and 2240 MPa and high-alloy steels it was between 440 and 2585 MPa. Ranges for aluminum and titanium alloys were quite different. Values of ultimate strength of aluminum alloys were between 73 and 580 MPa while those of titanium alloys covered the range between 434 and 1236 MPa. Number of steels with lower values of ultimate strength was highest in all three groups (unalloyed, low-alloy and high-alloy). With slight exception of low-alloy group, distribution of R_m within individual groups was quite similar as well so it was concluded that this could not have caused significant bias in analysis results.

Analysis of variance (ANOVA) of fatigue parameters for steels

Already Bäumel and Seeger [9] concluded that aluminum and titanium alloys should be considered separately from steels so this was not the part of further investigations here. However, practice evident in all existing estimation methods supports hypothesis that there is no significant statistical difference among values of fatigue parameters of unalloyed, low-alloyed and high-alloyed steel materials. However, performing one-way ANOVA analysis revealed that in fact statisticaly significant differences exist between steel groups regarding fatigue strength coefficient σ_f' ($F(2,264)=7,42$; $p<0,05$), fatigue strength exponent b ($F(2,264)=25,34$; $p<0,05$) and fatigue ductility exponent ($F(2,264)=12,61$; $p<0,05$). For fatigue ductility coefficient ε_f', no statisticaly significant difference could be determined to exist ($F(2,264)=1,32$; $p>0,05$). In order to further determine exactly which pairs of material groups are statisticaly significantly different, multiple Mann-Whitney U tests with Bonferroni correction should be performed.

Comparison of calculated strain-life curves

For all materials within each material group under consideration, numbers of load reversals to crack initiation $2N_f$ were calculated for 8 different values of total strain amplitude ($\Delta\varepsilon/2$ = 0,0015 , 0,002 , 0,0025 , 0,0035 , 0,005 , 0,009 , 0,015 , 0,02). To facilitate comparison of strain-life behavior of different material groups, logarithmic values of results obtained for three characteristic values of total strain amplitudes

($\Delta\varepsilon/2 = 0{,}0015$, $0{,}005$, $0{,}015$) are presented in form of $R_m - \log(2N_f)$ diagrams on Figures 1-3.

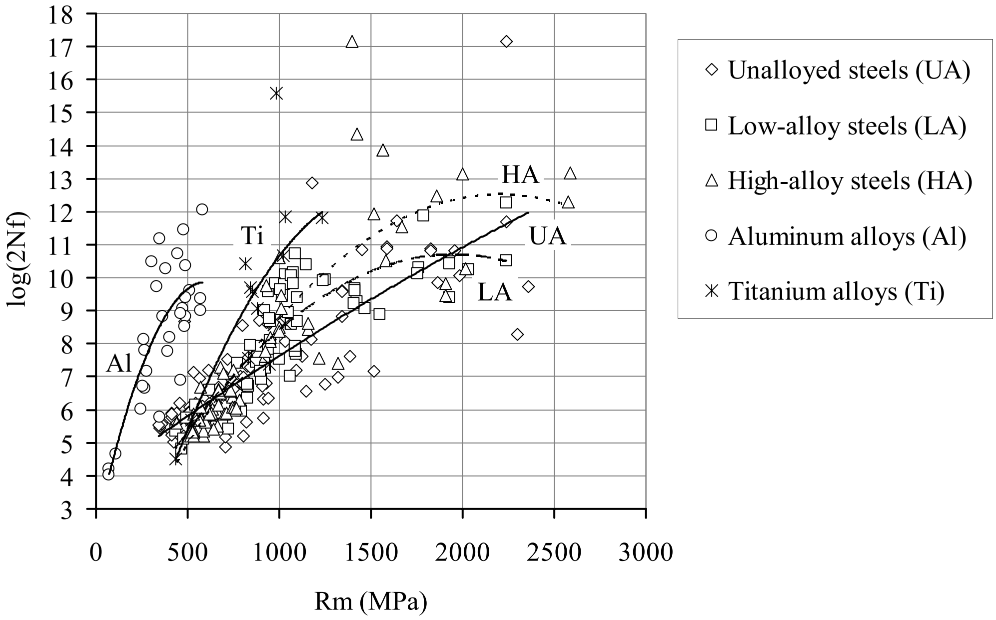

Figure 1. Load reversals $\log(2N_f)$ calculated for total strain amplitude $\Delta\varepsilon/2 = 0{,}0015$.

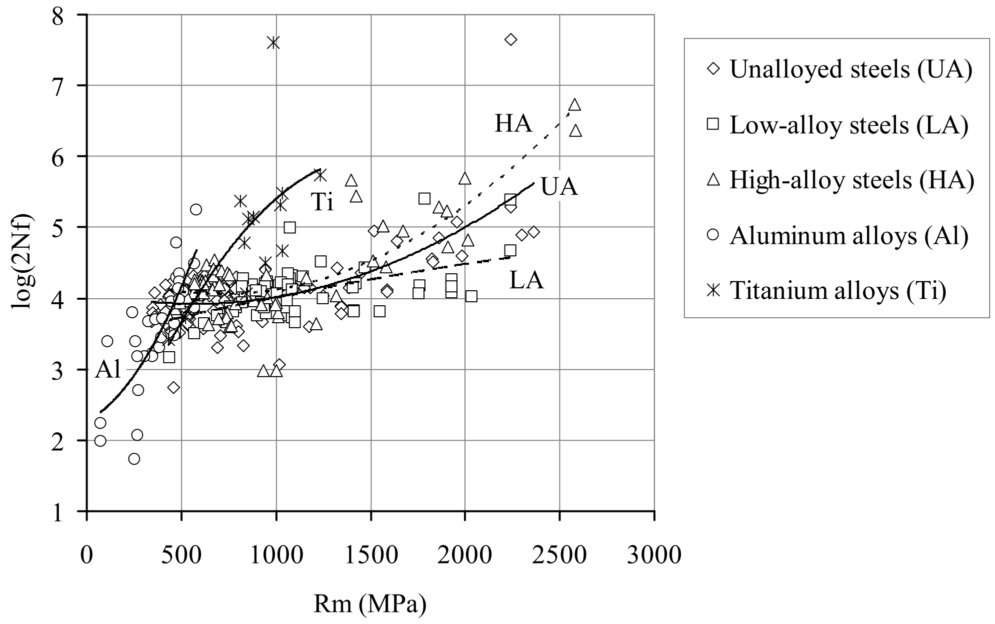

Figure 2. Load reversals $\log(2N_f)$ calculated for total strain amplitude $\Delta\varepsilon/2 = 0{,}005$.

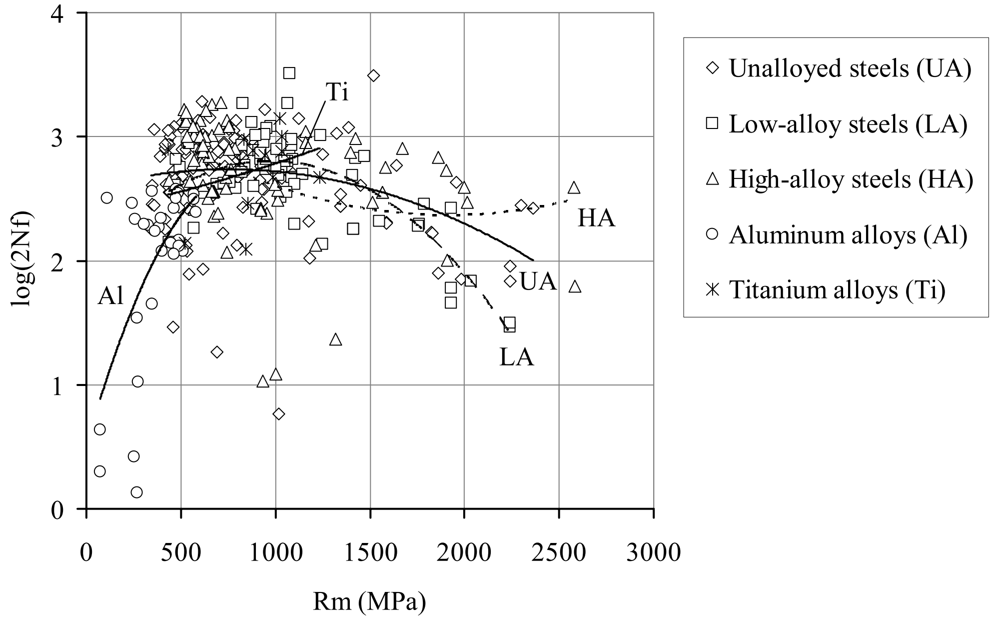

Figure 3. Load reversals $\log(2N_f)$ calculated for total strain amplitude $\Delta\varepsilon/2 = 0{,}015$.

With slight exception of [9] in which use of common expression is proposed for both unalloyed and low-alloyed steels, work presented in [7, 8, 10, 11, 12] suggests that steels need not be divided in subgroups for the purpose of fatigue parameters estimation. For further investigation of this hypothesis, best fit curves of quadratic type were calculated by means of nonlinear regression using $\log(2N_f)$ data for each steel group separately as well as for data on unalloyed and low-alloyed steels (UA+LA) and, using all available data on all steel groups (UA+LA+HA). In order to identify whether these "common" curves are appropriate for characterisation of strain-life behavior of individual steel groups, standard error of estimate (SEE) was used:

$$(SEE) = \sqrt{\frac{\sum_{i=1}^{n} \hat{\varepsilon}_i^2}{n-2}} \tag{1}$$

where n is number of data points and $\hat{\varepsilon}_i$ is individual residual value. Values of standard error of estimate SEE were calculated for every steel group separately, first using their corresponding best fit curves, then using best fit curve for unalloyed and low-alloy steels (UA+LA) and, finally, using best fit curve determined using data on all steel materials (UA+LA+HA). Values of (SEE) calculated for different values of total strain amplitude $\Delta\varepsilon/2$ and for all steel groups are given in Tables 2-4. It is evident that with exception of unalloyed steels, "common" curves are considerably inferior to the original ones calculated using $\log(2N_f)$ data of each steel group.

Table 2. Standard error of estimate (SEE) calculated for unalloyed steels group (UA)

$\Delta\varepsilon/2$	Standard error of estimate (SEE)				
	Best fit UA	Best fit UA+LA	Diff. (%)	Best fit UA+LA+HA	Diff. (%)
0,0015	**1,072**	1,098	2,43	1,137	6,06
0,002	**0,787**	0,8	1,65	0,832	5,72
0,0025	**0,609**	0,615	0,99	0,636	4,43
0,0035	**0,439**	0,441	0,46	0,444	1,14
0,005	**0,355**	0,361	1,69	0,356	0,28
0,009	**0,331**	0,338	2,11	0,334	0,91
0,015	**0,384**	0,389	1,3	0,386	0,52
0,02	**0,419**	0,423	0,95	0,421	0,48

Table 3. Standard error of estimate (SEE) calculated for low-alloy steels group (LA)

$\Delta\varepsilon/2$	Standard error of estimate (SEE)				
	Best fit LA	Best fit UA+LA	Diff. (%)	Best fit UA+LA+HA	Diff. (%)
0,0015	**0,936**	1,02	8,97	0,993	6,09
0,002	**0,675**	0,729	8	0,719	6,52
0,0025	**0,5**	0,535	7	0,552	10,4
0,0035	**0,369**	0,394	6,78	0,429	16,26
0,005	**0,31**	0,341	10	0,375	20,97
0,009	**0,239**	0,271	13,39	0,312	30,54
0,015	**0,253**	0,275	8,7	0,305	20,55
0,02	**0,269**	0,29	7,81	0,319	18,59

Table 4. Standard error of estimate (SEE) calculated for high-alloy steels group (HA)

$\Delta\varepsilon/2$	Standard error of estimate (SEE)				
	Best fit HA	Best fit UA+LA	Diff. (%)	Best fit UA+LA+HA	Diff. (%)
0,0015	**1,299**	-	-	1,434	10,39
0,002	**1,068**	-	-	1,177	10,21
0,0025	**0,894**	-	-	0,985	10,18
0,0035	**0,626**	-	-	0,689	10,06
0,005	**0,368**	-	-	0,407	10,6
0,009	**0,344**	-	-	0,382	11,05
0,015	**0,411**	-	-	0,438	6,57
0,02	**0,456**	-	-	0,480	5,26

CONCLUSION

Most of the existing methods for estimation of fatigue parameters do not discern materials by the alloy family i.e. metallic material group they belong to. However, comparison of strain-life behavior of unalloyed, low-alloyed and high-alloyed steels as well as that of aluminum and titanium alloys done in this work, indicates that significant differences exist among them. This is also substantiated by results of statistical analysis of fatigue parameters of different steel materials. Furthermore, calculated values of standard error of estimate (SEE) were significantly higher if combined data of all steel groups were used as a basis of estimate of strain-life behavior of individual steel material group. From this, it can be concluded that differential approach to the problem of strain-life fatigue parameters estimation is desirable and that it could be notably more effective than the one on which most existing methods are based. Individual expressions developed in such a manner could result in more accurate fatigue parameter estimations and hence, more accurate calculations of number of load reversals to crack initiation both in uniaxial and multiaxial fatigue conditions.

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