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Simple expressions to estimate the Manson–Coffin curves of ductile cast irons

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ABSTRACT

Due to the possibility of improving and adjusting their mechanical properties using austempering heat treatments, ductile cast irons are very attractive materials for structural applications. However, for this class of materials, very few fatigue data are available for designers in the International Standards. Therefore, at least in the preliminary design phase, simple expressions to estimate the fatigue properties of these materials, taking advantage of their static properties, can be useful for designers. In the recent literature, a simple method was proposed to estimate the strain-life curve of steels based only on the Brinell hardness and the elastic modulus of the material. In this paper, the possibility of extending this approach to ductile cast irons is discussed based on a set of more than 130 fatigue data obtained by the author on ferritic, pearlitic, isothermed and austempered ductile irons.

1. Introduction

Despite the growing number of applications of as-cast and heat-treated ductile cast irons in structural applications, such as connecting roads, support brackets, and drive trains for wind turbines, very few fatigue data for these materials are available for designers in the International Standards [1] or technical literature [2]. Over the last years, several researchers have focused their attention on understanding the fatigue behaviour of ductile cast irons [3–29]. However, to the author's knowledge, neither methodologies for evaluating the fatigue properties of ductile cast irons from their static data are available nor that proposed for steels and/or aluminium and titanium alloys [30–45] have not been extended to these materials. In fact, at least for preliminary design purposes, such correlations are desirable to reduce the time and costs associated with material fatigue testing.

Previous works [46,47] investigated the push–pull, constant amplitude, strain-controlled fatigue behaviour of ferritic, pearlitic as-cast (DIs), isothermed (IDIs) and austempered (ADIs) ductile cast irons, characterised by an engineering tensile strength R_m ranging from 400 MPa to 1300 MPa. In more detail, in [46], the material parameters appearing in the strain-life (Manson–Coffin curve) as well as in the cyclic stress–strain curve were calculated, taking into account the classical *compatibility* conditions [48] that involve stress/strain quantities. A more comprehensive method to evaluate the aforementioned material parameters was proposed in [47], according to the approaches previously proposed by Feltner and Morrow [49], Morrow [50], Halford [51] and Ellyin [52], which assumed the plastic strain hysteresis energy as a fatigue damage index. Therefore, in [47], the material parameters appearing in the plastic strain energy-based curves as well as in the classic Manson–Coffin curves were calculated using a set of so-called '*full compatibility*' expressions [50], which ensure the analytical coherence between the strain-life and energy-life equations. It was found that for all tested materials, it is possible to adopt a unique value of the fatigue strength exponent b ($b = -0.077$) and the fatigue ductility exponent c ($c = -0.565$).

In this paper, after a literature survey of the available methods developed to evaluate the strain-life curves of a material from its static data, some simple expressions useful for designers, at least in the preliminary design, are proposed according to the method suggested by Roessle and Fatemi [38] for steels. As a result, for the materials analysed in this paper, it is possible to estimate their fatigue properties by starting from the Brinell hardness and the elastic modulus.

2. A short review on the estimation methods for strain-life curves

The local strain approach is one of the methods available to predict the crack nucleation life, especially when finite element analyses are used to design complex structures. This approach relates the applied strain amplitude to the number of reversals to failure,

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Nomenclature

b	fatigue strength exponent	R_{p02}	0.2% offset yield strength
c	fatigue ductility exponent	$\Delta\varepsilon$	cyclic total strain range
E	elastic modulus measured from a static tensile test	ε_a	cyclic total strain amplitude (half the range $\Delta\varepsilon$)
E'	dynamic elastic modulus	ε_{ap}	cyclic plastic strain amplitude (half the range $\Delta\varepsilon_p$)
n	cyclic strain hardening exponent	ε_{ae}	cyclic elastic strain amplitude (half the range $\Delta\varepsilon_e$)
N_f	number of strain cycles to failure (half the number of reversals)	ε_f	true strain at final fracture, $\ln\left(\frac{1}{1-\mathrm{RA}}\right)$
RA	reduction in area	ε'_f	fatigue ductility coefficient
R_m	tensile strength	σ_f	true fracture strength
		σ'_f	fatigue strength coefficient

according to the Basquin, Manson and Coffin equations [53–55], in which the applied strain range $\Delta\varepsilon$ is divided in its elastic $\Delta\varepsilon_e$ and plastic $\Delta\varepsilon_p$ components:

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{\sigma'_f}{E'} \cdot (2N_f)^b + \varepsilon'_f \cdot (2N_f)^c \quad (1)$$

where $2N_f$ is the number of reversals to strain failure; σ'_f is the fatigue strength coefficient, calculated as the value of the stress amplitude for $2N_f = 1$; b is the fatigue strength exponent, evaluated as the slope of the line $\log(\Delta\sigma/2)$ against $\log(2N_f)$; ε'_f is the fatigue ductility coefficient, defined as the value of the plastic strain component for $2N_f = 1$; c is the fatigue ductility exponent, calculated as the slope of the line $\log(\Delta\varepsilon_p/2)$ against $\log(2N_f)$ and E' is the material dynamic elastic modulus. Besides E', Eq. (1) contains four material parameters (σ'_f, b, ε'_f and c) that define the strain life curve. Due to the reduced variation of E′ with respect to the elastic modulus measured from a static tensile test E, E' is usually assumed to be equal to E in Eq. (1).

Manson [30] first proposed two methods, the four-point correlation method and the universal slope method, to evaluate the strain-life curves. In the former method, the elastic and the plastic curves can be evaluated by locating two points of each of them. In this model, every point is determined from tensile static data, namely, σ_f, E and ε_f. In the latter method, the slopes of the plastic and elastic lines are universalised for all materials ($c = -0.6$; $b = -0.12$), while σ'_f and ε'_f are thought of as dependent on R_m and σ_f, respectively. This method was derived based on axial strain-controlled fatigue tests conducted on 29 materials. Among these materials are 20 steels, titanium and aluminium alloys, silver, beryllium and magnesium, covering a range of tensile strengths from 110 to over 2700 MPa, a range of reductions in area covering from 1 to 94%, high and low notch sensitivity, and cyclic-hardening and –softening characteristics. Over ten years later, Mitchell [31] proposed to correlate σ'_f to σ_f and ε'_f to ε_f, whereas b was linked to the tensile strength of the material. He further recommended constructing the plastic line using an empirical representation of the hardness versus transition fatigue life $2N_t$, instead of using a specific value of c. However, as the hardness-transition life data are not always available, Socie et al. [32] proposed a constant value of $c = -0.6$ for "ductile material" ($\varepsilon_f \cong 1$) and $c = -0.5$ for a "strong metal with $\varepsilon_f \cong 0.5$". Later, Muralidharan and Manson [33] proposed the modified universal slope method to improve the original universal slope method. This approach, developed based on 47 materials, provided lower universalised slopes for the elastic and plastic line ($b = -0.09$; $c = -0.56$) with respect to the original method. Moreover, both σ'_f and ε'_f are correlated to R_m and E, as suggested in [30], indicating that the material tensile strength has a significant effect on the low-cyclic fatigue regime. Bäumel and Seeger [34] proposed an alternative method, based on a large amount of fatigue data, called the "uniform material law". This model assigns different slopes to unalloyed and low-alloy steels and to aluminium and titanium alloys, confirming the idea that b and c can be considered as constants, at least for classes of materials. In this model, two different expressions for strain-life curves are used for unalloyed and low-alloy steels and for aluminium and titanium alloys. One advantage of this last men-

Table 1
Estimation methods for strain-life curves.

Method	Material	b	c	σ'_f (MPa)	ε'_f
Manson [30]	All materials	$\frac{\log(0.36 \cdot R_m/\sigma_f)}{5.60}$	$\frac{1}{3}\log\frac{0.0066-\sigma'_f\cdot(2\cdot10^4)^b/E}{0.239\cdot\{\ln[1/(1-RA)]\}^{3/4}}$	$1.25 \cdot [Rm \cdot (1+\varepsilon_f)] \cdot 2^b$	$\frac{0.125}{20^c} \cdot \left[\ln\left(\frac{1}{1-RA}\right)\right]^{3/4}$
Manson [30]	All materials	-0.12	-0.6	$1.9 \cdot R_m$	$0.76 \cdot \left[\ln\left(\frac{1}{1-RA}\right)\right]^{0.6}$
Mitchell [31] and Socie et al. [32]	For steels with HB < 500	$-\frac{1}{6} \cdot \log\left[\frac{2\cdot(R_m+345)}{R_m}\right]$	-0.6 ("ductile") or -0.5 ("strong")	$R_m + 345$ (MPa)	ε_f
Muralidharan and Manson [33]	All materials	-0.09	-0.56	$0.623 \cdot E \cdot \left(\frac{R_m}{E}\right)^{0.832}$	$0.0196 \cdot \ln\left(\frac{1}{1-RA}\right)^{0.155} \cdot \left(\frac{R_m}{E}\right)^{-0.53}$
Baumel and Seeger [34]	Unalloyed and low-alloy steels	-0.087	-0.58	$1.50 \cdot R_m$	0.59 if $R_m/E \leqslant 0.003$ or 0.811–73.8·R_m/E if $R_m/E > 0.003$
	Aluminium and titanium alloys	-0.095	-0.69	$1.67 \cdot R_m$	0.35
Ong [36]	Steels	$\frac{1}{6} \cdot \left\{\log\left[0.16 \cdot \left(\frac{R_m}{E}\right)\right] - \log\left(\frac{\sigma_f}{E}\right)\right\}$	$\frac{1}{4}\log\frac{0.0074-\sigma'_f\cdot(10^4)^b/E}{2.074\cdot\varepsilon_f}$	σ_f	ε_f
Roessle and Fatemi [38]	Steels with 150 < HB < 700	-0.09	-0.56	$4.25 \cdot \mathrm{HB} + 225$ (MPa)	$\frac{0.32\cdot\mathrm{HB}^2-487\cdot\mathrm{HB}+191000}{E}$
Meggiolaro and Castro [42]	Steels	-0.09	-0.59	$1.50 \cdot R_m$	0.45
	Aluminium alloys	-0.11	-0.66	$1.9 \cdot R_m$	0.28