JMEPEG (2011) 20:1323–1329
DOI: 10.1007/s11665-010-9765-3

A Modified Method to Estimate Fatigue Parameters of Wrought Aluminum Alloys

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(Submitted May 23, 2010; in revised form July 31, 2010)

Several methods for estimating fatigue properties of wrought aluminum alloys from simple tensile data or hardness were discussed. Among them, Park-Song's modified Mitchell's method provided the best estimation results in low fatigue life regime. Roessle-Fatemi's hardness method tends to be very erroneous in the present estimations. None of the investigated methods provide the satisfactory estimation results in the case of $N_f > 3 \times 10^4$ cycles. Besides, correlation between ultimate tensile strength and Brinell hardness was developed. Then, the modified Mitchell's method utilizing the ultimate tensile strength predicted from Brinell hardness was proposed in this study and successfully applied to estimate fatigue properties for wrought aluminum alloys. This simple method requires only Brinell hardness and modulus of elasticity as inputs, both of which are either commonly available or easily measurable. Prediction capability of this method was evaluated for wrought aluminum alloys with hardness between 120 and 157 HB. Results show that the proposed method provides the best life predictions for wrought aluminum alloys.

Keywords estimation methods, fatigue properties, hardness, wrought aluminum alloys

1. Introduction

Fatigue analysis plays an important role in the design of mechanical structures and components. Fatigue properties are usually obtained by performing fatigue tests on companion specimens of materials. However, fatigue tests not only require a lot of time and effort but also require a great deal of finances. Therefore, over the years, many researchers have attempted to estimate fatigue properties of materials from simple monotonic tensile data and/or hardness. If reliable correlations with reasonable accuracy can be established, durability performance predictions and/or optimization analyses can be performed, while substantially reducing time and cost associated with material fatigue testing.

Among estimation methods of fatigue properties, Manson (Ref 1) proposed two widely used methods, namely, the four-point correlation method and the universal slopes method. Mitchell (Ref 2) proposed another method, particularly suitable for steels. Muralidharan and Manson (Ref 3) proposed a new method to improve the universal slopes method, refer to here as the modified universal slopes method. In Ref 4, Bäumel and Seeger proposed another method, namely, uniform material law. Ong (Ref 5) proposed a modified four-point correlation method and Meggiolaro and Castro (Ref 6) proposed a new estimation method called as the medians method. Roessle and Fatemi (Ref 7) proposed an estimation method using hardness of materials, and Park and Song (Ref 8) proposed a new method for aluminum alloys though modifying the Mitchell's method. Among these methods, the modified universal slopes method (Ref 3), uniform material law (Ref 4), and Meggiolaro-Castro's medians method (Ref 6) require only ultimate tensile strength (σ_b) and the elastic modulus (E) data of material. Roessle-Fatemi's hardness method (Ref 7) requires only Brinell hardness (HB) and modulus of elasticity. Compared with the other methods, the four estimation methods are easier to apply.

As for these estimation methods of fatigue properties, several studies have been conducted to evaluate the accuracy or predictability. Park and Song (Ref 9) evaluated quantitatively all methods proposed until 1995 using the test data of 116 steels, 16 aluminum alloys, and 6 titanium alloys. Among the six estimated methods (i.e., the four-point correlation method (Ref 1), the universal slopes method (Ref 1), Mitchell's method (Ref 2), the modified universal slopes method (Ref 3), the uniform material law (Ref 4), and the modified four-point correlation method (Ref 5)), they found that the modified universal slopes method (Ref 3) is the best for unalloyed and high-alloy steels. Mitchell's method (Ref 2) is the best for aluminum alloys, while Ong's modified four-point correlation method (Ref 5) is the best for titanium alloys. In the latter articles, Song et al. (Ref 8, 10) show that their modified Mitchell's method is the best for the aluminum alloys. Roessle and Fatemi (Ref 7) reported that their hardness method is somewhat better than the modified universal slopes method, using the data obtained from 69 steels. Kim et al. (Ref 11) have evaluated seven estimation methods show that the uniform material law (Ref 4) and hardness method (Ref 7) provide better results, for alloy steels. Quite recently, Lee and Song (Ref 12) discussed several methods for estimating fatigue properties from hardness. Results show that the hardness method (Ref 7) proposed by Roessle and Fatemi provides excellent estimation results for steels. The so-called indirect hardness methods (Ref 12) utilizing the ultimate tensile strength predicted from Vickers hardness successfully applied to estimate fatigue

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properties for aluminum alloys and titanium alloys. It can be said from the above evaluation studies that Roessle-Fatemi's hardness method provide excellent results for steels, and the Mitchell's method and Park-Song's modified Mitchell's method give good results for aluminum alloys.

In this study, nine aforementioned methods were evaluated for estimating uniaxial fatigue properties from tensile data or hardness. The comparison was based on approximately 120 experimental data taken from the technical literature and generated by testing 11 different wrought aluminum alloys. In addition, correlation between the ultimate tensile strength and the Brinell hardness was established. Then, the modified Mitchell's method was corrected using the established correlation with reasonable accuracy.

2. Evaluation of Nine Estimation Methods for Wrought Aluminum Alloys

As mentioned previously, there are a total of nine estimation methods and among them, Mitchell's method and Park-Song's modified Mitchell's method provide relatively good results for aluminum alloys. The strain life curve is expressed as follows:

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{\sigma_f'}{E}(2N_f)^b + \varepsilon_f'(2N_f)^c \qquad \text{(Eq 1)}$$

where $\Delta\varepsilon/2$, $\Delta\varepsilon_e/2$, and $\Delta\varepsilon_p/2$ are total, elastic, and plastic strain amplitudes, respectively. σ_f' and b are fatigue strength coefficient and fatigue strength exponent, respectively, ε_f' and c are fatigue ductility coefficient and fatigue ductility exponent, respectively. Obviously, if the four fatigue parameters are available, the fatigue lifetime can be estimated by Eq 1. Several estimates of Manson-Coffin's parameters have been proposed in the literatures. The estimation methods to be discussed in this article are listed in Table 1. In this table, ε_f is the true fracture ductility. σ_f is the fracture strength. HB is the Brinell hardness. To evaluate an estimation method, some criteria are necessary. One of these criteria most frequently used is the error criterion which evaluates the predictability of an estimation method in terms of the fraction of data falling within a scatter band of a certain specified factor s. The evaluation value based on the error criterion, $E(s)$, is given as (Ref 8-10):

$$E(s) = \frac{\text{Number of data falling within } \frac{1}{s} \le \frac{N_p}{N_t} \le s}{\text{Number of total data}} \qquad \text{(Eq 2)}$$

where N_p and N_t are the predicted and experimental lives, respectively. It can be seen from Eq 2, the closer the $E(s)$ is to unity, the better the prediction is.

To evaluate the predictability of the aforementioned nine estimation methods, fatigue lives of the wrought aluminum alloys were predicted using the experimental strain-life data obtained from Ref (Ref 13-17). The mechanical properties of the wrought aluminum alloys are listed in Table 2. Figure 1, 2, 3, 4, 5, 6, 7, 8, 9 show the results of life predictions obtained on wrought aluminum alloys by the nine estimation methods. In these figures, the dotted lines, dashed lines, and dashed-dotted lines represent the factor-of-two, factor-of-five, and factor-of-ten boundaries, respectively. The perfect correlation line is expressed by the solid line.

It can be seen from Fig. 1, the predicted data by the four-point correlation method tend to give somewhat conservative

Table 1 Estimation methods for Manson-Coffin's parameters

Evaluation methods	σ_f'	ε_f'	b	c
Four-point correlation method (Ref 1)	$1.12\sigma_b\left(\frac{\sigma_f}{\sigma_b}\right)^{0.893}$	$0.413\varepsilon_f\left[1 - 81.8\left(\frac{\sigma_b}{E}\right)\left(\frac{\sigma_f}{\sigma_b}\right)^{0.179}\right]^{-1/3}$	$-0.0792 - 0.179\log\left(\frac{\sigma_f}{\sigma_b}\right)$	$-0.52 - \frac{1}{4}\log(\varepsilon_f) + \frac{1}{3}\log\left[1 - 81.8\left(\frac{\sigma_b}{E}\right)\left(\frac{\sigma_f}{\sigma_b}\right)^{0.179}\right]$
Universal slopes method (Ref 1)	$1.9018\sigma_b$	$0.7579\varepsilon_f^{0.6}$	-0.12	-0.6
Mitchell's method (Ref 2)	$\sigma_b + 345$	ε_f	$-\frac{1}{6}\log\left[\frac{2(\sigma_b+345)}{\sigma_b}\right]$	-0.6
Modified universal slopes method (Ref 3)	$E \times 0.623\left(\frac{\sigma_b}{E}\right)^{0.832}$	$0.0196\varepsilon_f^{0.155}\left(\frac{\sigma_b}{E}\right)^{-0.53}$	-0.09	-0.56
Uniform material law (Ref 4)	$1.67\sigma_b$	0.35	-0.095	-0.69
Modified four-point correlation method(a) (Ref 5)	$\sigma_b(1 + \varepsilon_f)$	ε_f	$\frac{1}{6}\left\{\log\left[0.16\left(\frac{\sigma_b}{E}\right)^{0.81}\right] - \log\left(\frac{\sigma_f}{E}\right)\right\}$	$\frac{1}{4}\log\left(\frac{0.00737 - \Delta\varepsilon_e^*/2}{2.074}\right) - \log\varepsilon_f$
Medians method (Ref 6)	$1.9\sigma_b$	0.28	-0.11	-0.66
Hardness method (Ref 7)	$4.25\mathrm{HB} + 225$	$\frac{0.32\mathrm{HB}^2 - 487\mathrm{HB} + 191000}{E}$	-0.09	-0.56
Modified Mitchell's method (Ref 8)	$\sigma_b + 355$	ε_f	$-\frac{1}{6}\log\left(\frac{\sigma_b+355}{0.446\sigma_b}\right)$	-0.664

(a) $\Delta\varepsilon_e^* = \frac{2\sigma_f}{E}\left[10^{\frac{2}{3}\left\{\log\left[0.16(\sigma_b/E)^{0.81}\right] - \log(\sigma_f/E)\right\}}\right]$

Table 2 Summary of monotonic tensile data for wrought aluminum alloys

Materials	E, MPa	σ_b, MPa	σ_y, MPa	σ_f, MPa	HB	RA, %	ε_f, %	Ref
2014-T6	68950	510	462	627	135	25	29	(13)
2024-T4	70329	476	303	634	120	35	43	(13)
7075-T6	71018	579	469	745	150	33	41	(13)
LC9CgS3	72179.5	560.2	518.2	748.47	157	21	28.34	(13)
LC4CS	72571.8	613.9	570.8	710.62	150	16.6	18	(13)
LY12CZ (plate)	71022.3	475.6	331.5	618.04	126	26.6	30.19	(13)
LY12CZ (rod)	73160.2	545.1	399.5	643.14	131	16.5	18	(13)
AA-2014-T6(a)	74352.12	534	485.07	667.5	135	25	28.8	(14)
LY12CZ (tube)	73000	545	400	643	…	…	18	(15)
AA-2024-T351(a)	69591	482.3	358.29	602.87	120	25	28.8	(16)
7075-T651(a)	71700	561	501	724.25	…	29.1	34.4	(17)

(a) The true fracture ductility calculated from $-\ln(1 - \mathrm{RA}/100)$, and the fracture strength calculated from $(1 + \mathrm{RA}/100)\sigma_b$

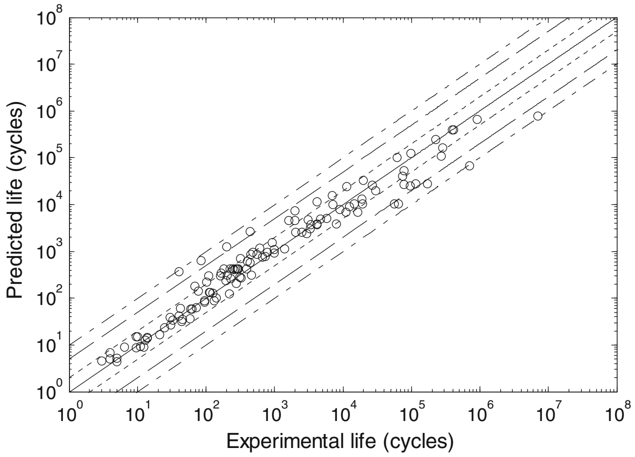

Fig. 1 Prediction of fatigue life by the four-point correlation method (Ref 13-17)

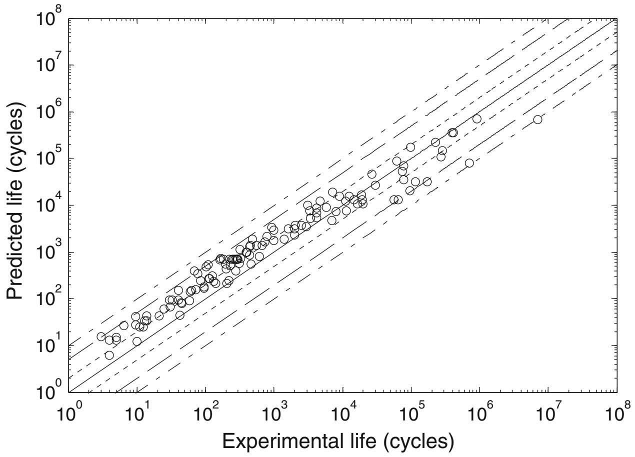

Fig. 2 Prediction of fatigue life by the universal slopes method (Ref 13-17)

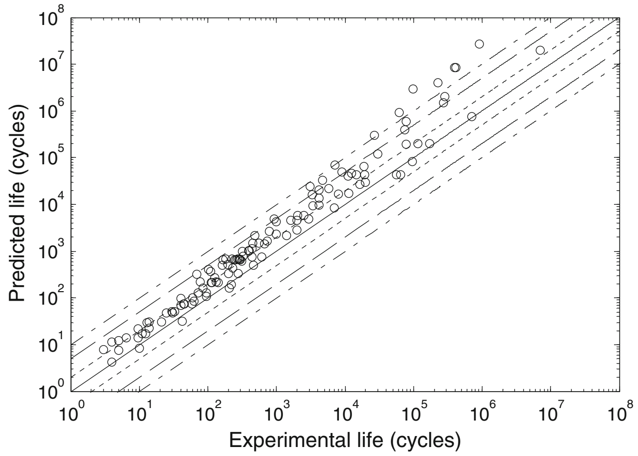

Fig. 3 Prediction of fatigue life by the Mitchell's method (Ref 13-17)

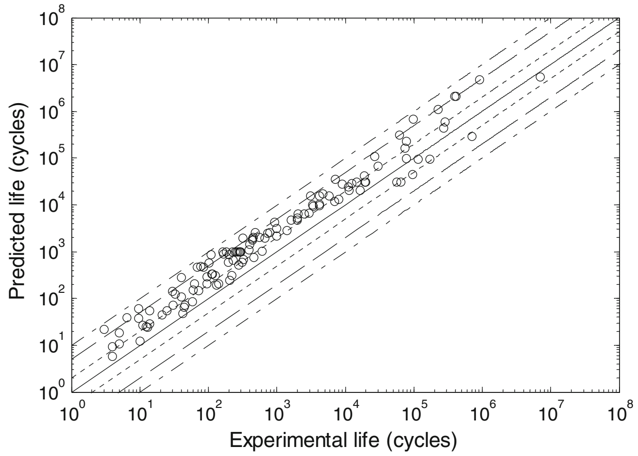

Fig. 4 Prediction of fatigue life by the modified universal slopes method (Ref 13-17)

life predictions in the long-life range. Such a trend is also discernible in the result for the universal slopes method shown in Fig. 2. What is different from the four-point correlation method is that the predicted data by the universal slopes method tend to be nonconservative in the low cycle fatigue regime. By the way, the same trend is also observed in the results for the Mitchell's method and modified universal slopes method (see Fig. 3, 4, respectively). As for uniform material law, modified

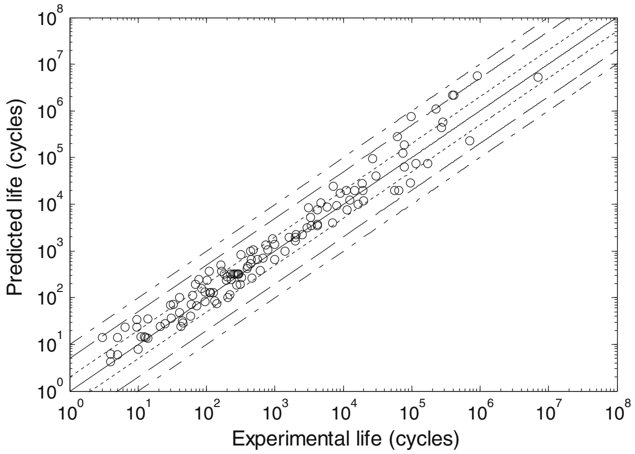

Fig. 5 Prediction of fatigue life by the uniform material law (Ref 13-17)

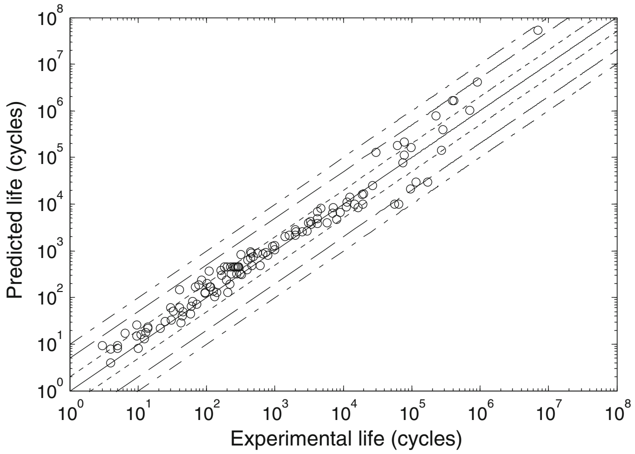

Fig. 6 Prediction of fatigue life by the modified four-point correlation method (Ref 13-17)

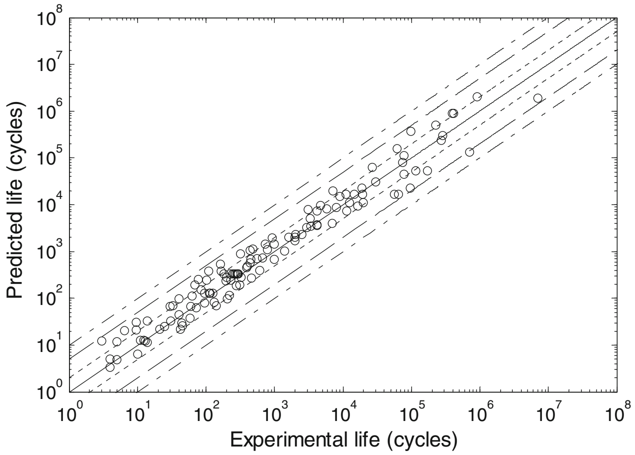

Fig. 7 Prediction of fatigue life by the medians method (Ref 13-17)

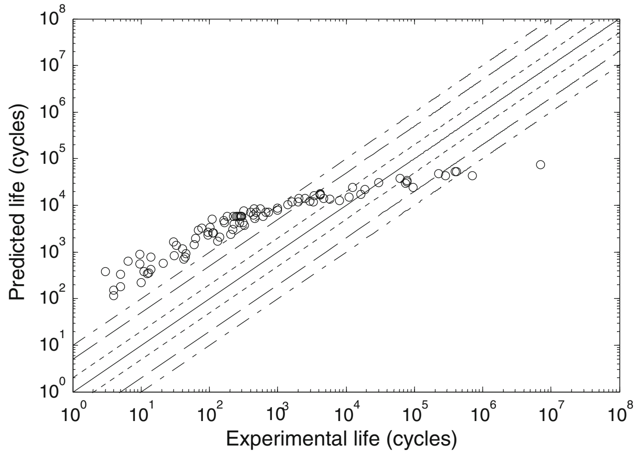

Fig. 8 Prediction of fatigue life by the hardness method (Ref 13-17)

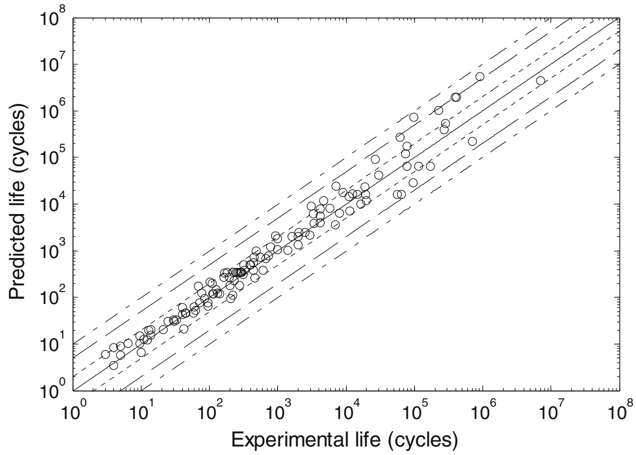

Fig. 9 Prediction of fatigue life by the modified Mitchell's method (Ref 13-17)

four-point correlation method and medians method, most of the predicted data in short-life range provide relatively good life predictions with slightly nonconservative. However, the predicted results are more scattered in the long-life range. In addition, it can be found from Fig. 8, the test data of wrought aluminum alloys predicted by Roessle-Fatemi's hardness method tend to be very erroneous in many instances, considerably. In more detail, the hardness method tends to give considerably non-conservative predicted lives in the short-life range; however, the predicted data tend to level off in the long-life range, resulting in over-conservative life predictions. Among the nine estimation methods, the modified Mitchell's method proposed by Park and Song gives the best predictions in the low fatigue life regime. However, the predicted results in longer-life range are unsatisfactory.

3. Estimating Fatigue Properties from Brinell Hardness for Wrought Aluminum Alloys

3.1 Correlation Between the Ultimate Tensile Strength and the Brinell Hardness

As mentioned previously, it is often desirable to estimate fatigue behavior of a material from easily and quickly

Table 3 Data used for comparison of the ultimate tensile strength (Ref 20)

Materials	σ_b, MPa	HB
LD2CS	347	111
LD5CS	365	100
LD7CS	431	130
LD10CS	430	120
LF2M (rod)	186	45
LF2Y2 (rod)	245	60
LF3M (plate)	220	58
LF3Y2 (plate)	297	75
LF5M (plate)	297	65
LF10M	265	70
LF21M (plate)	105	30
LF21Y2 (plate)	163	40
LY1CZ	294	70
LY1M	157	38
LY2CS	513	135
LY11CZ	402	115

obtainable material properties such as hardness with reasonable degree of accuracy. As for aluminum alloys, JSMS (Ref 18) has proposed the following equation to estimate the ultimate tensile strength using the Vicker hardness (HV):

$$\sigma_b = \frac{(\mathrm{HV} - 21.9)}{0.242}\ (\mathrm{MPa}) \qquad \text{(Eq 3)}$$

For aluminum alloys, the following conversion between Brinell hardness and Vicker hardness has been proposed in ASTM Standard (E140-97) (Ref 19):

$$\mathrm{HV} = -2.9744 + 1.2005\mathrm{HB} \quad \text{for } 40 \le \mathrm{HB} < 160 \qquad \text{(Eq 4)}$$

Then, Eq 3 can be rewritten as:

$$\sigma_b = \frac{(1.2005\mathrm{HB} - 24.8744)}{0.242}\ (\mathrm{MPa}) \quad \text{for } 40 \le \mathrm{HB} < 160 \qquad \text{(Eq 5)}$$

The method for estimating the ultimate tensile strength from Brinell hardness shown in Eq 5 was evaluated, using the data listed in Table 2 and 3. The experimental data listed in Table 3 are taken from Ref 20. A plot of ultimate tensile strength versus Brinell hardness was provided in Fig. 10. It may be seen from this figure, there is a poor agreement between the experimental data and the predictions obtained from Eq 5. A linear least squares fit through the data with $R^2 = 0.96$ results in the following correlation:

$$\sigma_b = 3.66\mathrm{HB} + 15.8\ (\mathrm{MPa}) \qquad \text{(Eq 6)}$$

3.2 A Modified Method to Estimate Fatigue Properties

The four fatigue properties, i.e., fatigue strength coefficient, σ'_f, fatigue strength exponent, b, fatigue ductility coefficient, ε'_f, and fatigue ductility exponent, c, are defined in Eq 1. It can be seen from Eq 1, a change in each fatigue property affects a fatigue life prediction. In this article, we assumed that Manson-Coffin equation (Eq 1) estimated each fatigue property of LC4CS aluminum alloy (Ref 13) by 20% greater or less than the experimental value. The four experimental fatigue properties (σ'_f, b, ε'_f, c) equal to 884.69 MPa, −0.0727, 0.2452 and −0.7761, respectively, which were taken from Ref 13. Comparison of influence of each fatigue property on life prediction as a factor of scatter at $N_f = 1$ and $N_f = 10^8$ is plotted in Fig. 11. In this figure, the horizontal abscissa stands for the value predicted by Manson-coffin equation with the four fatigue properties equal to 884.69 MPa, −0.0727, 0.2452, and −0.7761, respectively, and the dotted lines, dashed lines, dashed-dotted lines represent the factor-of-two, factor-of-five, and factor-of-ten boundaries, respectively. The perfect correlation line was expressed by the solid line. As can be seen from Fig. 11, the fatigue ductility coefficient, ε'_f, has very little influence on a life prediction. But, the change of both the strength coefficient, σ'_f, and the strength exponent, b, have substantial effect on the life prediction. Therefore, both the precisely strength coefficient and the precisely strength exponent are the keys to exactly predict the fatigue life.

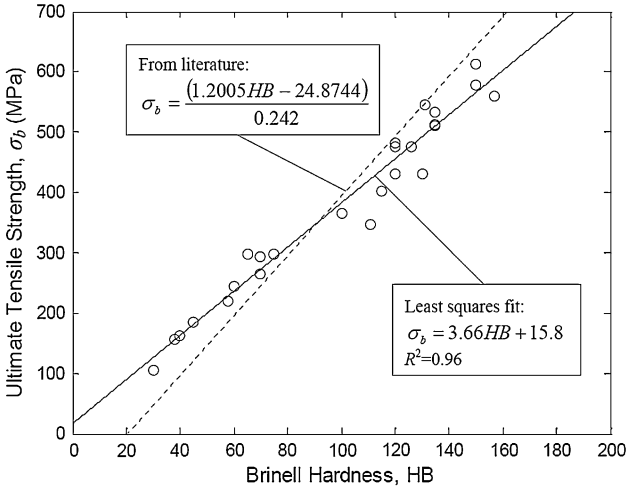

Fig. 10 Ultimate tensile strength versus Brinell hardness (Ref 13-17, 20)

Although Park-Song's modified Mitchell's method is the best among the nine estimation methods, it gives the unsatisfactory results in longer-life range (see Fig. 9). In this study, Park-Song's modified Mitchell's method for estimation of fatigue properties was corrected with the predicted ultimate tensile strength, σ_b, from Brinell hardness (Eq 6). Furthermore, if the fact that the average value of the fracture ductility listed in Table 2 equals to 0.281 is considered, then, the Modified Mitchell's method proposed by Park and Song can be rewritten as follows:

$$\frac{\Delta\varepsilon}{2} = \frac{3.66\mathrm{HB} + 370.8}{E}(2N_f)^{-\frac{1}{6}\log[(3.66\mathrm{HB}+370.8)/(1.632\mathrm{HB}+7.047)]} + 0.281(2N_f)^{-0.664} \qquad \text{(Eq 7)}$$

Here, the average value of fracture ductility was adopted on the basis the fact that the fatigue ductility coefficient has little influence on the fatigue life prediction (see Fig. 11c). This indirect hardness method (Eq 7) refers to here as hardness-modified Mitchell's method. Predicted data by hardness-modified Mitchell's method was compared to the experimental data in Fig. 12. Equation 7 relates the four fatigue parameters only to the Brinell hardness. Therefore, if the Brinell hardness is known, the four fatigue parameters can be estimated, and the fatigue life can be predicted.

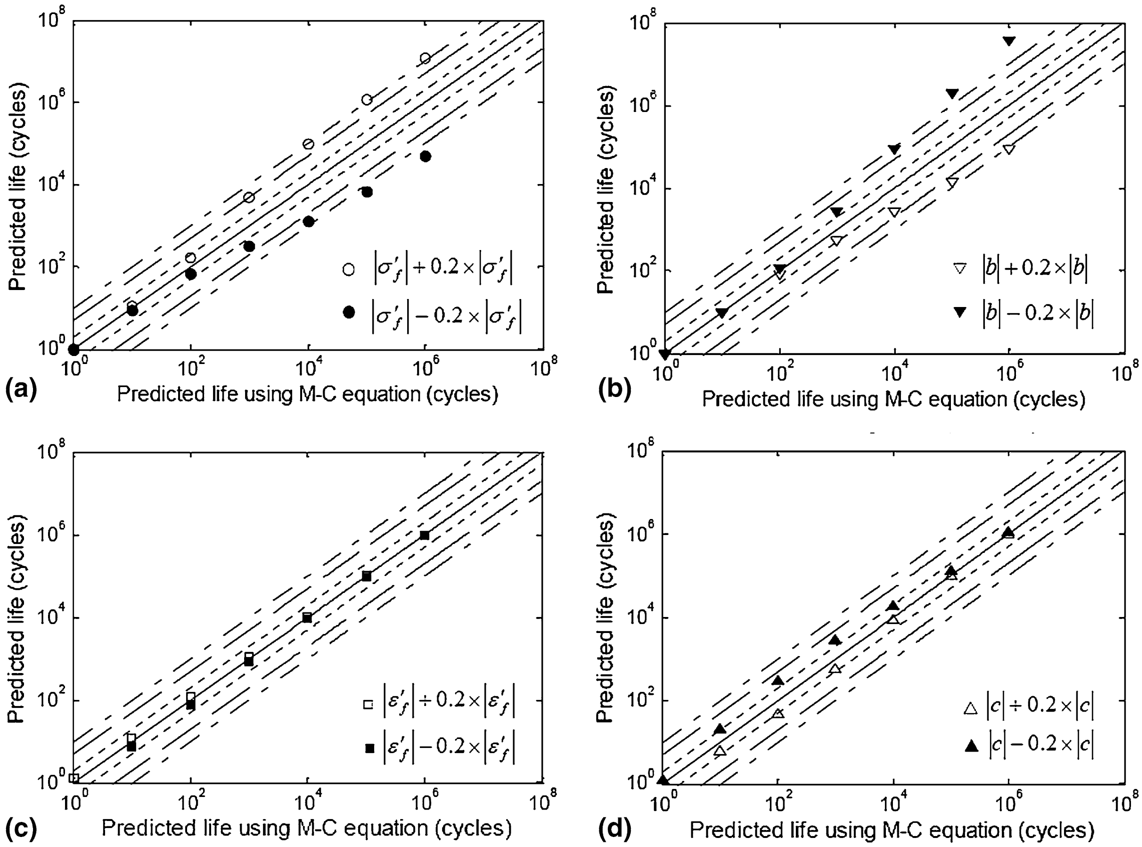

Fig. 11 Comparison of influence of each fatigue property on life prediction: (a) fatigue strength coefficient, (b) fatigue strength exponent, (c) fatigue ductility coefficient, (d) fatigue ductility exponent

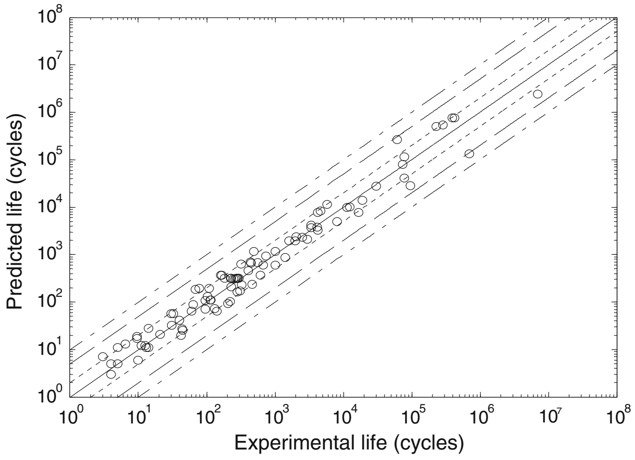

Fig. 12 Prediction of fatigue life by the hardness-modified Mitchell's method (Ref 13-17)

Table 4 Comparison of estimation methods in terms of evaluation values

Evaluation methods	$E(s = 2)$	$E(s = 3)$	$E(s = 5)$	$E(s = 10)$
Four-point correlation method	0.779	0.902	0.926	0.992
Universal slopes method	0.426	0.762	0.959	0.992
Mitchell's method	0.402	0.705	0.869	0.943
Modified universal slopes method	0.230	0.574	0.844	1.000
Uniform material law	0.705	0.861	0.967	1.000
Modified four-point correlation method	0.762	0.885	0.967	1.000
Medians method	0.689	0.893	0.992	1.000
Hardness method	0.075	0.118	0.215	0.344
Modified Mitchell's method	0.803	0.902	0.975	1.000
Hardness-modified Mitchell's method	0.807	0.968	0.989	1.000

It can be seen from Fig. 12, the predictive accuracy of the hardness-modified Mitchell's method is considered superior to the other methods. In order to clearly show the predictability of various estimation methods, Table 4 showed comparisons of the predictive accuracy of estimation methods on the basis of the evaluation values defined in Eq 2. It can be seen from Table 4, in contrast to the modified Mitchell's method, the hardness-modified Mitchell's method results in relatively accurate and somewhat better predictions, especially in the case of $N_f > 3 \times 10^4$ cycles. For example, 96.8% of the predicted lives based on the hardness-modified Mitchell's method are within a life factor range of ±3, while 90.2% of the predicted lives are within this life factor range for the modified Mitchell's method. The evaluation value of fraction of data $E(s = 2)$ is 80.7% for the hardness-modified Mitchell's method, which is somewhat better than the modified Mitchell's method. It should be emphasized that the hardness-modified Mitchell's method only requires hardness and modulus of elasticity of the material.

4. Conclusion

For aluminum alloys, the prediction capabilities of various methods developed to estimate fatigue properties from simple tensile data was quantitatively evaluated. Based on the discussions in the preceding sections, the following conclusion can be drawn:

(1) Park-Song's modified Mitchell's method can estimate fatigue properties well for wrought aluminum alloys in low-to-intermediate fatigue life regime, while the predicted results are scattered in high fatigue life regime. Roessle-Fatemi's hardness method is the worst method used to evaluate the fatigue properties of wrought aluminum alloys.

(2) A strong correlation exists between hardness and ultimate tensile strength of wrought aluminum alloys. A linear relationship was found to provide a good fit to the data.

$$\sigma_b = 3.66\mathrm{HB} + 15.8$$

(3) A new method, namely the hardness-modified Mitchell's method was proposed to estimate the fatigue properties of wrought aluminum alloys, as the fraction of data falling within a factor of 3 scatter band was about 97%. It should be mentioned here that this method only requires hardness and modulus of elasticity as inputs, both of which were either commonly available or easily measurable.

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