Available online at www.sciencedirect.com
ScienceDirect
Trans. Nonferrous Met. Soc. China 28(2018) 1226−1232
Transactions of Nonferrous Metals Society of China
www.tnmsc.cn

Development of fatigue analytical model of automotive dynamic parts made of semi-solid aluminum alloys

Kh. A. RAGAB[1,2], A. BOUAICHA[1], M. BOUAZARA[1]

1. Applied Sciences, University of Quebec at Chicoutimi, Saguenay, Quebec, Canada;
2. Metallurgical Engineering, Cairo University, Egypt

Received 17 April 2017; accepted 30 September 2017

Abstract: Automotive suspension control arm is used to join the steering knuckle to the vehicle frame. Its main function is to provide stability under fatigue stresses of loading and unloading in accelerating and braking. Conventionally, these parts were made of steel; however, fuel consumption and emission of polluting gases are strongly dependent on car weight. Recently, there is a try to develop and design much lighter and better fatigue resistant metal of semisolid A357 aluminum alloys. This work aims at a better understanding of identifying the fatigue strain-hardening parameters used for determining fatigue characteristics of aluminum suspension control arm using analytical and mathematical modeling. The most judicious method is to perform the fatigue tests on standardized test pieces and then plot two Wohler curves, mainly number of cycles as a function of the stress and as a function of the deformation. From these curves and following a certain mathematical and analytical methods, certain curves are plotted and then all of these coefficients are drawn. The new calculated parameters showed a clear improvement of the fatigue curve towards the experimental curve performed on the samples of aluminum alloy A357 compared with the same analytical curve for the same alloy.

Key words: fatigue; aluminum; semisolid; analytical modeling; qualitative analysis

1 Introduction

Fatigue failure is considered to be the most common problem occurred in automotive engineering parts that work continuously in dynamic as in case of control arms of the suspension system. This type of failures occurs under conditions of dynamic loading and it occurs without any obvious warning resulting in sudden failures [1,2]. The fatigue failure is divided into four stages starting with cyclic stresses, crack initiation, crack propagation, and fracture. Fluctuating stress cycles, that cause fatigue failure, may be occurred by completely reversed stress cycles, repeated stress cycles and random stress cycle. The latter is considered as complicated stress cycles that may be applied to automotive engineering parts that work continuously in dynamic as suspension control arm. The basic method for presenting fatigue behavior of engineering materials is to plot the S−N curve, which is a plot of stress (S) against the number of cycles to failure (N). The stress value is related to mean stress value $(\sigma_{\max}+\sigma_{\min})/2$ or alternating stress (σ_A). The fatigue life curve is determined for a specified value of mean stress σ_m and stress ratio R [3−5].

Fatigue life prediction methods are classified according to three approaches, namely deformation, strength, and energy [6,7]. The deformation approaches are generally intended for fatigue with low number of cycles. Probably the most widely used approach in this category is that developed by Manson−Coffin [7]. In the field of olygocyclic fatigue, plastic deformations are the most dominant. For a uniaxial stress state, their curve connects the number of the cycles at the break, N_r, to the amplitude of the plastic strain, $\Delta\varepsilon_p/2$. In the case where plastic deformations are negligible in the presence of elastic deformations, the Basquin model is used. From the two previous relations, one can finally derive the Manson−Coffin−Basquin relation that gives the total elastic and plastic deformation as a function of the number of cycles at break (N_r). Note that the following relation holds for R=−1 [5−7]:

$$(\varepsilon_t)_{\text{Manson-Coffin}}=\varepsilon_e+\varepsilon_p=\frac{\sigma_f'}{E}(2N_r)^b+\varepsilon_f'(2N_r)^c \tag{1}$$

where b and c are fatigue strength exponent and fatigue

Corresponding author: Kh. A. RAGAB; Tel: +418-5455011(2501); Fax : +418-545-5012; E-mail: khaled.ragab@uqac.ca
DOI: 10.1016/S1003-6326(18)64760-0

ductility exponent, respectively; σ_f' and ε_f' are fatigue strength coefficient and fatigue ductility coefficient, respectively; N_r is the number of cycles to rupture; ε_a is the strain amplitude and E is the elastic modulus. Smith, Watson and Topper (SWT) [8−10] developed an energy approach, based on the use of an exit of a product damage variable stress−strain. Regarding analytical approach, Smith−Watson−Topper has developed an energy method by way of a damage variable extracted from the stress−strain product ($\sigma_{max}\cdot\varepsilon_a$); this is known as the strain energy density criterion as discussed by the following equation. The calculation of the total deformation ε_a for this type of materials is related to the Ramberg−Osgood relationship [8−11]:

$$(\varepsilon_a)_{\text{Ramberg−Osgood}} = \varepsilon_{\text{elastic}} + \varepsilon_{\text{plastic}} = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{H'}\right)^{1/n'} \tag{2}$$

It is defined that H' is the cyclic strength coefficient and n' is the cyclic hardening exponent. In this work, an attempt was made to analyze some methods of predicting the fatigue lifetime. To this end, the different methods existing in the literature that link the number of N cycles to maximum stresses and deformations were evaluated in this work. This is for the purpose of having the most appropriate relationship to apply it to the model of the suspension control part. The calculation of number of cycles N enables an approximate assessment of the lifetime of the suspension arm studied, which will facilitate the subsequent analysis of the results obtained later in the experimental tests.

2 Fabrication and testing procedures

The applicable parts were prepared, for material characterization, using the SEED-rheocast semi-solid casting process from A357 aluminum alloy billets (Al−7%Si−0.6%Mg). The alloys, received in the form of ingots, were melted in a silicon carbide crucible of 150 kg capacity, using an electric resistance furnace. The molten metal of the desired composition is transferred to a vessel whose thermal mass is sufficient to cool the melt. The vessel and its contents are swirled at 200 r/min, where the swirled enthalpy equilibration device process involves two main steps: at first, the heat is extracted to achieve the desired liquid−solid mixture, and then the excessive liquid is drained to produce a self-supporting semisolid slug that is formed under pressure. The principal is based on achieving rapid thermal equilibrium between the metallic container and the bulk of the metal by proper process parameter selection such as pouring temperature, eccentric mechanical stirring, and drainage of a portion of eutectic liquid. The SEED process is coupled with a high pressure die casting (HPDC) press to produce parts of traditional and/or modified design of a lower arm suspension system of A357 alloys used for mechanical characterizations. The parts were subjected to a T6 heat treatment by applying solution treatment at 540 °C for 8 h followed by water quench at 65 °C and artificial aging at 170 °C for 5 h, as this type of temper offers optimal fatigue strength. Fatigue tests were performed on full-scale parts (arm) on a servohydraulic machine in sinusoidal force control at room temperature at a frequency of 1 Hz. Sinusoidal load form was used with varied peak stress and compressive loads from ±105 to ±280 MPa with variations in displacement from ±1 to ±2 mm, as shown in Fig. 1 [8,10,12,13]. Metallographic specimens were extracted and polished using standard procedures and examined using a scanning electron microscope (SEM); the fatigue fracture surface was investigated.

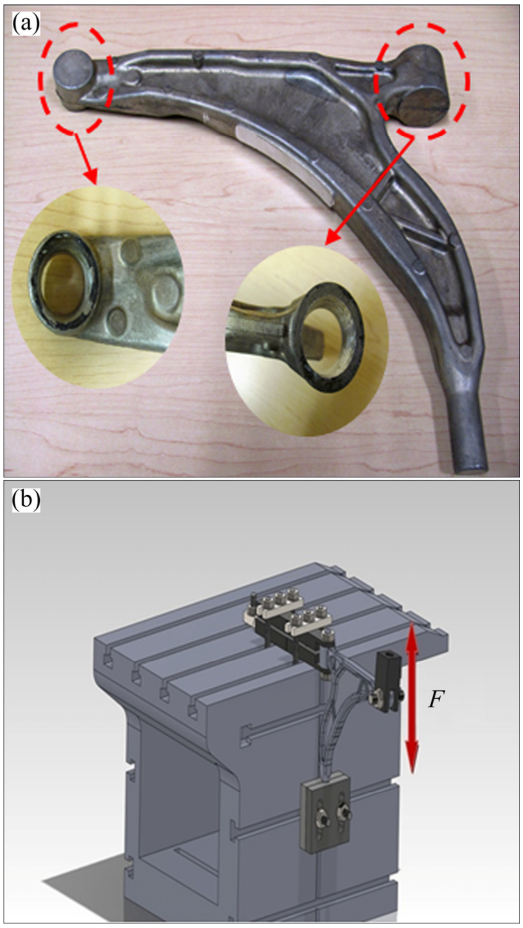

Fig. 1 Suspension control arm part (a) tested by fatigue servohydraulic machine (b)

3 Results and discussion

3.1 Development of fatigue analytical model

According to the literature, it became clear that the model proposed by Manson−Coffin is the closest one to predict the fatigue lifetime of A357 semisolid alloy. Such alloys are commonly known for their high ductility from

10% to 12% after the standard heat treatment process. The results obtained, using this fatigue model, are more accurate for low cycle fatigue conditions with fully-reversed loading conditions. The parameter coefficients in this formula are related to a given material; the application of Manson−Coffin model requires that the material be completely defined by such coefficients. The challenge experienced is that the coefficients are not available for semi-solid alloy A357, which makes it necessary to be calculated.

According to previous studies [8,10,12,14−16] applied to various aluminum alloys, the six fatigue parameters and coefficients (b, c, $\acute{\varepsilon}_f$, $\acute{\sigma}_f$, $\acute{H}$ and $\acute{n}$) as well as ultimate strength (σ_u) were identified. These results were used in this work to set up mathematical relationships between the different parameters of the fatigue analytical model for semisolid A357 aluminum alloys. Most of the mathematical relationships of significant fatigue results show a linear relationship between the coefficients. Only the fatigue strain exponent (c) as a function of its coefficient ($\acute{\varepsilon}_f$) revealed a logarithmic relation. The first constructed model is for $\acute{\sigma}_f$ as a function of σ_u, where 28 samples were used, as shown in Fig. 2. Figure 2 shows a linear relationship between these two parameters giving the following equation with a coefficient of determination R^2=0.8058.

$$\acute{\sigma}_f = 2.2617\sigma_u - 125.6 \tag{3}$$

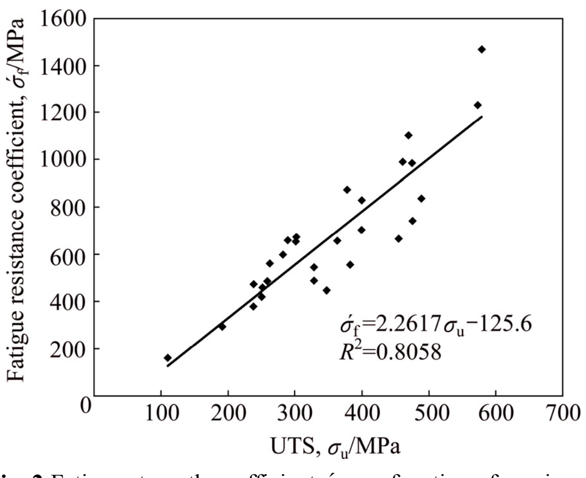

Fig. 2 Fatigue strength coefficient $\acute{\sigma}_f$ as a function of maximum tensile strength σ_u

Since the ultimate stress (σ_u) of the semi-solid A357 aluminum is known, then the approximate value of ($\acute{\sigma}_f$) can be deduced from the previous equation, making σ_f in this case equal to 672.78 MPa. Similarly, for this second case, a linear relationship was drawn between the cyclic resistance coefficient ($\acute{H}$) and the maximum tensile strength (σ_u). When the number of samples is 27, a coefficient of determination obtained is higher, R^2=0.9471, as shown in Fig. 3(a), where the resulting line follows the pace of the following equation:

$$\acute{H} = 1.6875\sigma_u - 93.127 \tag{4}$$

According to Eq. (4), the cyclic resistance coefficient ($\acute{H}$) for semi-solid A357 material in this work will be approximately 502.56 MPa. The correlation of the fatigue strain exponent (c) and coefficient ($\acute{\varepsilon}_f$) was assessed with 37 samples, as shown in Fig. 3(b). The curve obtained is in logarithmic form according to the equation above, with a satisfactory coefficient of determination either R^2=0.8804.

$$c = -0.127\ln \acute{\varepsilon}_f - 0.8398 \tag{5}$$

Using 30 samples, the points relating the cyclic resistance coefficient (H) with cyclic hardening exponent ($\acute{n}$) gives linear relation, where R^2=0.8814, as shown in Fig. 3(c). The equation of this linear relation is indicated by the following equation:

$$\acute{H} = 7429\acute{n} + 76.712 \tag{6}$$

The $\acute{H}$ value for the semi-solid A357 aluminum was previously deduced from Eq. (4). Therefore, with this value of 502.56 MPa, the cyclic hardening exponent ($\acute{n}$) will have a value of 0.057. Concerning the following case, the exponent (b) and the fatigue strength coefficient ($\acute{\sigma}_f$) showed a linear relationship with a more or less high dispersion of the 31 selected samples. The coefficients were determined with the lowest value of R^2=0.7264, as shown in Fig. 3(d). The equation governing this linear variation is in the following form:

$$b = -6\times10^{-5}\acute{\sigma}_f - 0.0555 \tag{7}$$

Depending on the value of the fatigue strength coefficient $\acute{\sigma}_f$ calculated by Eq. (3), and in accordance with Eq. (7), fatigue strength exponent (b) will, in this case, be equal to −0.0958. Regarding the relationship between $\acute{n}$ and σ_u involving 30 samples, it provides a value of coefficient of 0.61. The linear relationship generated is used for comparison with the previous combinations. The linear equation is indicated by the following equation:

$$\sigma_u = 3953\acute{n} + 132.66 \tag{8}$$

So far, four of the six fatigue parameters have been clearly identified. First, b and $\acute{\sigma}_f$ were calculated relative to the experimental fatigue tests performed on standardized specimens in previous work related to this study [8,12]. Then, taking into account the relationships deduced between the maximum tensile strength (σ_u) and cyclic resistance coefficient ($\acute{H}$) and between this coefficient ($\acute{H}$) and the cyclic hardening exponent ($\acute{n}$), their respective values have been deduced. The significant lack is to clarify the values of the fatigue strain exponent (c) and the fatigue strain coefficient ($\acute{\varepsilon}_f$) at the moment. Regarding the calculations of these values, the following modeling method was adopted.

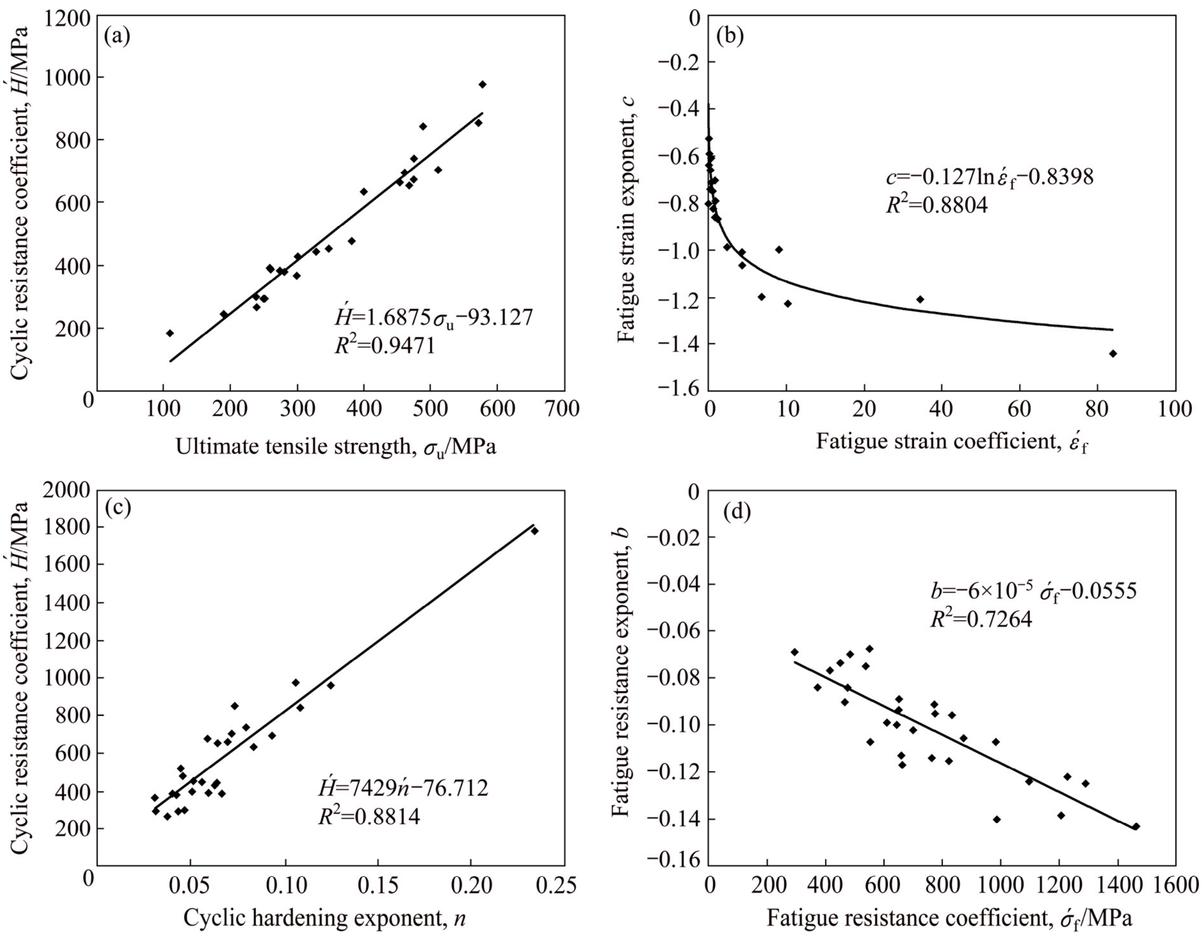

Fig. 3 Mathematical relationships between fatigue parameters and coefficients: (a) $\acute{H}-\sigma_u$; (b) $c-\acute{\varepsilon}_f$; (c) $\acute{H}-n$; (d) $b-\acute{\sigma}_f$

Using Matlab, when the parameters are changed in the established program, the coefficients ($\acute{H}$ and $\acute{\sigma}_f$) and the exponents (b and $\acute{n}$) are set at the calculated values of 502.56 MPa, 1327 MPa, 0.174 and 0.057, respectively. The values of $\acute{\varepsilon}_f$ and c are then varied to obtain a curve which approximates the experimental curve.

Following these analytical and mathematical approaches, the identification of fatigue parameters, for A357 semi-solid alloys, is necessary to determine the fatigue resistance coefficient using an analytical method for the fatigue experimental results of T6 heat-treated standard samples of aluminum alloys. A mathematical technique based on extrapolation was used to determine the rest of the coefficients. Thereafter, these results were compared with those obtained by experimental fatigue tests applied to suspension control arm of 1.5 kg in mass and to those obtained by Matlab modeling. All these results are optimized to get the final fatigue parameters applicable for A357 T6 heat-treated aluminum semisolid standard alloys and for suspension control arm, as given in Table 1. Finally, the Wöhler curves for the A357 SS material were traced to visualize the difference between analytical and the experimental result on standardized specimens. Since for a given sample the fatigue test never gives the same result twice then it is considered that the curves obtained are acceptable and that the coefficients taken from the preceding data are correct, as shown in Fig. 4. Table 2 indicates the fatigue properties of most common Al−Si−Mg heat treated alloys that were

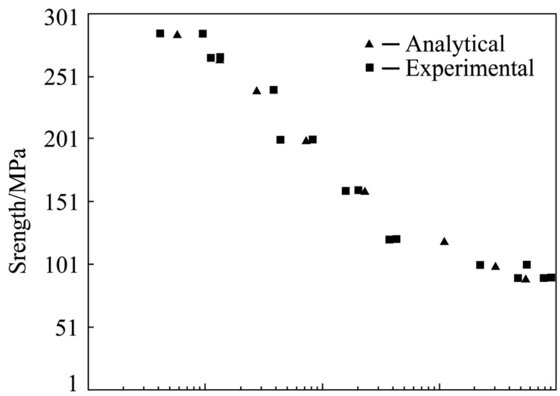

Fig. 4 Wohler curves of analytical study compared to experimental curve carried out on standard samples of A357 semisolid alloys

used for analytical and mathematical analysis in this work. These data were refined and modified, using Matlab modeling, to obtain the fatigue coefficients of A357 semisolid casting alloys used in fabrication of control arm suspension system.

3.2 Microstructure characteristics

Figure 5 shows the fatigue fracture surface using scanning electron microscope of the samples obtained from damaged parts due to fatigue failure. The fatigue fracture starts with cracks initiation, followed by crack

Table 1 Fatigue parameters and coefficients optimization for A357 semisolid alloys

A357-T6 semisolid alloy	σ'_f/MPa	ε'_f	b	c	H'	n'
Fatigue test applied to suspension control arm of 1.5 kg	1327		−0,174			
Approximate traits for fatigue results applied to T6 standard samples	672.78		−0.0958		502.95	0.057
Matlab modelling		0.13		−0.6		
Optimized values for applicable engineering part (suspension control arm)	1327	0.13	−0.174	−0.6	455	−0.066

Table 2 Classification of fatigue properties of Al−Mg−Si alloys as function of heat treatment T6 [3,8,10,15,16]

Alliage	σ_u/MPa	σ'_f/MPa	ε'_f	b	c	H'	n'
A356 T6	283	594	0.027	−0.124	−0.530	379	0.043
A357-T6	303	666	0.09	−0.117	−0.610	430	0.063
A357 SS-T6	353	1327		−0,172			
6082-T6	330	486.8	0.209	−0.07	−0.593	443.9	0.064
6060-T6	240	376.5	0.157	−0.084	−0.537	267.3	0.038
6061 T6	301	648.3	4.34	−0.1	−1.01	365.5	0.031
6009-T6	230	85.2	0.561	−0.0957	−0.746		
6010-T6	379	871.7	1.366	−0.106	−0.869		

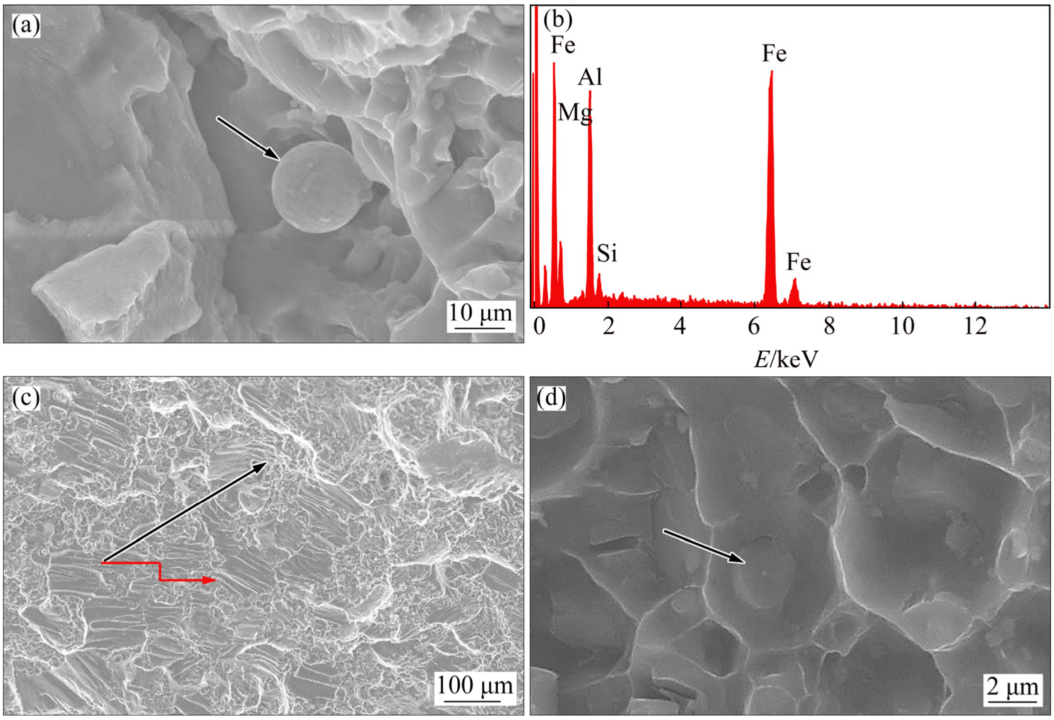

Fig. 5 Fracture surface analysis of aluminum semisolid suspension control arm casting samples using SEM microscopy (black and red arrows refer to crack initiation and propagation, respectively): (a) π-Fe intermetallics; (b) EDX spectrum; (c) Cracks initiation and propagation; (d) π-Fe intermetallics

propagation, as shown in Fig. 5(c), where black and red arrows refer to crack initiation and propagations, respectively. The crack propagation is controlled by localized plasticity, relating to casting technique and heat treatment process, which affects the microstructural heterogeneities, or the metal matrix constituents as mentioned in Ref. [16]. Fatigue failure occurred at specific weak positions in the part that was cast by a semisolid technique as indicated in previous work [8,12]. Figures 5(a) and (d) show the characteristics of Fe−π-$Al_8Mg_3FeSi_6$ intermetallics, which are formed in the A357 alloy castings, as identified by the EDX spectra. The spheroidization of π-$Al_8Mg_3FeSi_6$ phases resulting from the effect of the semi-solid casting process decreases their negative effect on fatigue strength. In addition to casting defects, the size and morphology of Fe-containing phases are the main sources of the detrimental effect on the fatigue mechanical properties of the castings. The morphology of these intermetallics produces high stress concentrations and constitutes a stress raiser resulting in a decrease in the crack initiation energy which affects negatively on fatigue strength of the alloys [13,17,18].

4 Conclusions

1) The fatigue parameters were determined using analytical and mathematical methods for experimental results of A357 semisolid castings. The new calculated parameters showed a clear improvement of the fatigue curve towards the experimental curve compared with the analytical curve for the alloy investigated.

2) The results demonstrate that the new calculated parameters may be used properly in fatigue models (Manson−Coffin−Basquin and/or SWT) to calculate fatigue life time or strength for semisolid A357 aluminum alloy. This may be applied under specific design parameters saving the time required for applying fatigue experimental tests.

3) Regarding fatigue failure characteristics using SEM microscopy, the spheroid morphology of π-Fe intermetallics is related to the positive effect of semisolid casting process.

References

[1] DIMATTEO N D. Fatigue and fracture [M]. Vol. 19. Materials Park, OH, USA: ASM International. The Materials Information Society, 1996.

[2] STEPHENS R I, FATEMI A, STEPHENS R R, FUCHS H O. Metal fatigue in engineering [M]. Toronto, Canada: John Wiley & Sons, 2000.

[3] STANZL-TSCHEGG S E, MAYER H R, BESTE A, KROLL S. Fatigue and fatigue crack propagation in AlSi7Mg cast alloys under in-service loading conditions [J]. International Journal of Fatigue, 1995, 17(2): 149−155.

[4] TING J C, LAWRENCE F V. Modeling the long-life fatigue behavior of a cast aluminum alloy [J]. Fatigue & Fracture of Engineering Materials & Structures, 1993, 16(6): 631−647.

[5] DIETER G E. Mechanical metallurgy, metallurgy and metallurgical engineering series [M]. 2nd Edition. New York: McGraw-Hill, 1976.

[6] OHAMA S, YOSHIMURA T, NOGUCHI H. Fatigue characteristics of aluminum cast alloy AC2B-T6 with cast skin [J]. WIT Transactions on Engineering Sciences, 2003, 40(3): 1−10.

[7] HALFORD G R. Fatigue and durability of structural materials [M]. Materials Park, Ohio, USA: ASM International, 2006.

[8] BOUAZARA M, BOUAICHA A, RAGAB Kh A. Fatigue characteristics and quality index of A357 type semi-solid aluminum castings used for automotive application [J]. Journal of Materials Engineering and Performance, 2015, 24(8): 3084−3092.

[9] INCE A, GLINKA G. A modification of Morrow and Smith−Watson−Topper mean stress correction models [J]. Fatigue & Fracture of Engineering Materials & Structures, 2011, 34(11): 854−867.

[10] SAOUDI A, BOUAZARA M, MARCEAU D. Study of the fatigue life and weight optimization of an automobile aluminium alloy part under random road excitation [J]. Shock and Vibration, 2010, 17(2): 107−121.

[11] SKELTON R P, MAIER H J, CHRIST H J. The Bauschinger effect, Masing model and the Ramberg–Osgood relation for cyclic deformation in metals [J]. Materials Science and Engineering A, 1997, 238(2): 377−390.

[12] BOUAZARA M, BANITALEBI H, RAGAB K A, MRAD H. On the characteristics of automotive low arm-suspension system parts made of aluminum casting alloys [J]. International Journal of Cast Metals Research, 2016, 29(3): 129−136.

[13] RAGAB K A, BOUAZARA M, BOUAICHA A, ALLAOUI O. Microstructural and mechanical features of aluminium semi-solid alloys made by rheocasting technique [J]. Materials Science and Technology, 2017, 33(6): 646−655.

[14] SAMUEL E, ZHENG Chang-Qing, BOUAICHA A, BOUAZARA M. Fatigue behavior in rheocast aluminum 357 suspension arms using the SEED process [C]//ICAA13 Pittsburgh Springer, Cham. Pittsburgh, 2012: 151−156.

[15] BORREGO L P, ABREU L M, COSTA J M, FERREIRA J M. Analysis of low cycle fatigue in AlMgSi aluminium alloys [J]. Engineering Failure Analysis, 2004, 11(5): 715−725.

[16] FATEMI A, PLASEIED A, KHOSROVANEH A K, TANNER D. Application of bi-linear log–log *S*–*N* model to strain-controlled fatigue data of aluminum alloys and its effect on life predictions [J]. International Journal of Fatigue, 2005, 27(9): 1040−1050.

[17] ROSSO M. The influence of casting process on quality and performances on Al based automotive components [C]//Proceedings of the 13th International Scientific Conference of Achievements in Mechanical & Materials Engineering. Gliwise-Wista, Poland, 2005: 547.

[18] WANG Q G, APELIAN D, LADOS D A. Fatigue behavior of A356/357 aluminum cast alloys. Part II–Effect of microstructural constituents [J]. Journal of Light Metals, 2001, 1(1): 85−97.

半固态铝合金汽车动力零件的疲劳分析模型开发

Kh. A. RAGAB[1,2], A. BOUAICHA[1], M. BOUAZARA[1]

1. Applied Sciences, University of Quebec at Chicoutimi, Saguenay, Quebec, Canada;
2. Metallurgical Engineering, Cairo University, Egypt

摘　要：汽车悬架控制臂被用来连接转向节和车架，其主要功能是在加速和制动的装载和脱载的疲劳应力作用下提供稳定性。一般情况下，这些零件采用钢材制备，导致油耗量和污染气体排放量增加。最近，有研究尝试研发更轻、更耐疲劳的半固态 A357 铝合金以取代钢质悬架控制臂。本研究旨在更好地理解运用数学模拟识别疲劳应变强化参数，以便确定铝合金悬架控制臂的疲劳特性。最佳的方法是对标准试样进行疲劳测试，然后以循环次数分别作为应力和变形的函数，绘制两条 Wohler 曲线。利用这些曲线和特定的数学分析方法，可以得到所有的参数。计算出的新参数表明，与同一合金的相同分析曲线相比，A357 铝合金样品的实验疲劳曲线明显改善。

关键词：疲劳；铝；半固态；分析模型；定性分析

(Edited by Bing YANG)