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Proposal of a stress-based isothermal LCF life model for Aluminium alloy cylinder heads

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Abstract

The paper presents and discusses the calibration procedure and the results related to a new easy-to-use low cycle fatigue (LCF) life prediction empirical stress-based model. The model was applied to a commercial Aluminium alloy diesel engine cylinder head. The material characterization was carried out on commercial cylinder heads made by primary AlSi9Cu1, investigating the mechanical properties on sets of specimens obtained from layers positioned at different distances from the gas face of the cylinder heads. The results of mechanical characterization and LCF model calibration parameters are presented for each layer. The material characterization was carried out at room temperature to assess the procedure and validate the model.

The life assessment performance of the model was compared with the corresponding Basquin-Manson-Coffin model. The model prediction fitted the experimental data trend with a determination coefficient ranging from 0.75 to 0.98, which is globally higher with respect to the parameter fitting obtained with the Basquin-Manson-Coffin calibration. Furthermore, all life forecasts are close to the experimental results with a variance lower than 55%. A future development of the research work with further material characterization at different temperature will allow to validate and discuss the temperature dependence of the model parameters and to investigate its thermo-Mechanical Fatigue (TMF) life assessment performance.

Keywords: Aluminium alloy; LCF; Damage; Life estimation

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Nomenclature

$A\%$	elongation to failure, in %
b, c	fatigue strength exponent and fatigue ductility exponent
E	Young modulus
N_f	number of cycles to failure (i.e. residual life)
R	stress ratio
R^2	determination coefficient
W_{tALSE}, W_{ALSE}	total dissipated energy and total approximated energy to failure
$2N_f$	number of reversal cycles to failure
α, β	ALSE model proportional coefficient and exponent
$\Delta\varepsilon_{mech}$, $\Delta\varepsilon_{el}$, $\Delta\varepsilon_{pl}$	total mechanical, elastic and plastic strain range
ΔW_t, ΔW_e, ΔW_p	total, elastic and plastic strain energy density
σ'_f, ε'_f	fatigue strength coefficient and fatigue ductility coefficient
$\dot{\varepsilon}_{pl}$	plastic strain rate
$\sigma_{max}(i)$	maximum nominal stress at cycle i
σ_{max}, σ_{min}	maximum and minimum nominal stress
$\overline{\sigma_{max}}$	equivalent stress

1. Introduction

A review of uniaxial damage models with reference to formulation, theoretical background and nomenclature, can be found in Delprete et al. (2008) and Zwang and Swansson (1998). According to experimental results obtained by researchers (e.g. Minichmayr (2007)) on Aluminum alloys, the Neu-Sehitoglu (NS) model (Neu, Sehitoglu (1989)) gives the best accuracy in comparison to many others models mainly based on energetic approaches. At low temperatures the pure fatigue mechanism controls lifetime; else creep and oxydation effects affect fatigue life. Chaboche model (Lemaitre and Chaboche (2002)) allows for a good representation of the mean stress influence on the fatigue life and correctly predicts the remaining life since it was successfully applied on Aluminum alloy specimens subjected on spectrum loading (Kaminski (2006)). The Basquin-Manson-Coffin (BMC) model is the most widely applied in practice. Due to its straightforward applicability, many researches implement the BMC model, at least for a first trial, to estimate, by means of a relatively limited experimental campaign, the residual life of specimens subjected to room temperature and isothermal LCF loading conditions (Neu and Sehitoglu (1989), Azadi (2013), Elhaari et al. (2015), Kahn et al. (2010), Lee et al. (2009), Srivatsan et al. (2004), Storlatz (2001)). The damage is computed by processing the total strain imposed on the specimen, without taking into account the oxidation contribution. For low temperature and isothermal conditions NS model and BMC model apply the same life estimation equations. In the investigated literature quantitative validation of the models reliability is limited.

Cylinder head is an important component of internal combustion engines. Due to its complex geometry, the cylinder head is obtained by a single cast of primary (high performance and diesel engines), secondary (gasoline engines) Aluminium alloys, and cast iron (industrial engines). With respect to life prediction, the cylinder head shows a further complexity due to the material properties that change in the volume, due to complex component geometry and to solidification and cooling phases of casting. Indeed, during mold filling and cooling, the component is subjected to strong and uneven thermal gradients, which in turn lead to the formation of different internal crystalline structures, as well as uneven residual strain and stress fields. According to the position inside the cylinder head volume, the material specimens will show different mechanical properties as well as different fatigue resistance

properties. Last but not least, literature damage models were mainly developed for steels and this fact can introduce a further uncertainty in the life estimation results for Aluminium components undergoing LCF.

The present research focuses on Aluminium alloys for which limited literature data on LCF behavior were reported (Emami et al. (2009), Kintzel et al. (2010, 2014), Rutecka et al. (2011), Xue et al. (2006), Lee et al. (2009), Engler-Pinto (2004)). Main aims are the analysis of mechanical and isothermal LCF behavior of a commercial Aluminum alloy cylinder head made by primary AlSi9Cu1, and the performance comparison between different life assessment models applied to the component. In the present paper, two life assessment models are compared for isothermal LCF life prevision of the Aluminum cylinder head under investigation. In particular, material properties are characterized at different distances from the gas face, the BMC model is calibrated for each layer, and the life estimation is performed for each layer. The same procedure is applied for a new proposed empirical stress-based model. The obtained results are then compared with the aim of comparing the life estimation performances and proposing an effective and cost reduction procedure to assess LCF isothermal life for complex components such as the cylinder head. In the present research, as far as the LCF regime is concerned, the main contribution on the damage is due to the plastic part of the total strain and it is assumed that the total mechanical strain range governs the LCF fatigue mechanism (ASTM E 606). Since the presented experimental tests are carried out in isothermal conditions, the life prediction relations do not take the thermal strain component into account.

2. Analytical background

The definition for the here presented parameters can also be found in ASTM E1823. According to ASTM E606, in the BMC model the strain life relation is described as the linear sum of two exponential functions, elastic and plastic:

$$\frac{\Delta\varepsilon_{mech}}{2} = \frac{\Delta\varepsilon_{el}}{2} + \frac{\Delta\varepsilon_{pl}}{2} = \frac{\sigma'_f}{E}\left(2N_f\right)^b + \varepsilon'_f\left(2N_f\right)^c \tag{1}$$

The model calibration can be obtained separately for the two parts by means of isothermal fatigue tests. According to ASTM E739 (1998) a continuous curve, which approximates the general data trend, can be obtained from the discrete data distribution by means of a linear data least square method regression. This model is implemented for Aluminium alloys in Elhadari (2011) but no validation of the model in life estimation is given.

The energetic approach is an alternative to the material constitutive description, to estimate the component life by means of a direct applicability. Model parameters are obtained from actual material hysteresis loops. Many energetic damage models were successfully applied on aluminum alloys by researchers (Song et al (2011), Azadi (2012), Tabibian et al (2012)). The energetic models introduce a strain energy density parameter that is generally related to the cycle to failure by means of exponential relations. Similarly to the approach followed for the BMC model, a continuous curve can be obtained to relate the strain energy density and the number of cycle to failure. In these models the fatigue resistance can be expressed as a function of the plastic strain energy density, where the material constant parameters can be obtained by means of a mono-linear regression analysis. According to the model proposed in Azadi (2013), the cumulative plastic strain energy can be obtained by summing the plastic strain energy per cycle over the whole fatigue cycles and linked to the number of cycles to failure; the material parameters can be determined by means of a linear regression of the experimental data.

According to these models, the dissipated plastic energy to failure is a material constant that is related to the loading conditions. It can be obtained both from midlife stress and strain data. The fatigue damage parameter is related to the number of cycles to failure by means of an exponential relation with N_f where proportionality coefficient and exponent are material parameters, determined by means of linear regression of the experimental data. It results that energy-based criterion is in good agreement with the experimental fatigue lifetime and the computed estimations and this agreement increases by taking into account of the hydrostatic pressure in the energy approach. Again, the behavior of the Aluminium alloys results to be strongly dependent on loading conditions.

To conceive a more effective damage model, a relation able to correlate a physical quantity describing the material loading condition with another quantity related to the fatigue resistance, is here proposed: the ALSE (Aluminium Life Stress-based Empirical) model, dedicated to Aluminium alloys. This empirical model refers to the energetic approach: the dissipated energy is related to the hysteresis cycles, which are related to stress and strain, and it is assumed that a threshold energy value is dissipated to reach failure in cyclic fatigue loading according to Skelton (1998). In strain controlled fatigue tests, the stress are assumed proportional to the dissipated energy and the total dissipated energy to failure is assumed proportional to the area subtended by the maximum cycle stresses versus cycles. According to Azadi (2012) the model parameters are calibrated from stress data acquired during strain controlled testing, but the total stress is considered both because the damage due to elastic straining is considered to induce damage and also to decrease possible errors induced by splitting elastic and plastic strains and stresses from experimental data. The parameter related to the total dissipated energy to failure, W_{tALSE}, is defined as the integral of the maximum stress over the cycles and can be approximated with a discrete summation:

$$W_{tALSE} = \int_1^{N_f} \sigma_{max}(N)\,dN \approx W_{ALSE} = \sum_{i=1}^{N_f-1} \sigma_{max}(i)\left(N_{i+1} - N_i\right) \tag{2}$$

where the maximum nominal stress at cycle i is measured by the load cell.

The empirical parameter W_{ALSE} takes into account of the actual material hardening or softening behavior. Experimental tests show that the total dissipated energy to failure W_{ALSE} is related to the plastic strain with an exponential relation which parameters are obtained by means of data fitting, layer by layer:

$$W_{ALSE} = \alpha\,e^{-\beta\Delta\varepsilon_{pl}} \tag{3}$$

Another model parameter, expressed in [MPa] and proportional to the energy dissipated to failure by the specimen, can be defined as:

$$\overline{\sigma_{max}} = \frac{1}{N_f}\sum_{i=1}^{N_f} \sigma_{max}(i) \tag{4}$$

where $\overline{\sigma_{max}}$ is the equivalent stress that would lead to failure if progressive cyclic damaging phenomena do not affect the hysteresis cycle shape.

In literature energetic empirical models refer to the dissipated energy measured by means of the hysteresis cycle. As example, Skelton (1998) states that the material fails under LCF when the dissipated energy reaches a threshold value. This dissipated energy can be computed as the cumulate of the hysteresis cycle areas versus the number of cycles. To obtain the threshold value, the stress and strain data need to be continuously acquired and calculated. If the loading condition change, a new complete testing campaign is needed to estimate this material parameter. In the ALSE model, the key parameter for life estimation is an equivalent stress, expressed in [MPa], that implies the material cyclic constitutive behavior, and that can be obtained by simple measurements during few LCF testing.

3. Materials and Methods

Some commercial cylinder heads made by AlSi9Cu1 primary alloy were cut in 10 slices 10 mm thick, parallel to the gas face (Fig. 1), and the specimens were obtained from these slices. The specimen geometry was chosen to extract the highest possible number of specimens from each cylinder head layer, at least six. For all the specimens extracted from the same layer, the same mechanical properties were assumed. Specimen dimensions and geometry, and statistical data processing procedures agree to the Standards ASTM E606 and ASTM E739 respectively. On each layer, three sets of experiments were performed. The first set aimed to obtain the material mechanical properties for

different distances from the gas face of the cylinder head (hardness measurements, monotonic tensile testing, micrographic characterization). The second set was carried out to calibrate the life models. The last set was performed to validate the model life estimations. For these two test sets, at room temperature testing was carried out: strain controlled LCF testing at different strain levels and strain ratio $R = -1$. It has to be noted that in experimental reports on this kind of components (i.e. Tabibian et al. 2013) specimens are obtained in generic location thus not taking into account of the variation of properties and LCF behavior through the component. The number of specimens to be tested was chosen according to the ASTM E739 that refers to the strain-life assessment; the same number of specimens was used for the other energy based life model. For research activity, confidence interval 95% and minimum percentage of replication 33%, a minimum of 6 specimens per layer is required. Three different strain levels were chosen with two repetitions (50% of replication) and 60 specimens were extracted. On layers where the complex geometry allowed obtaining less than 6 specimens, the model calibration was not possible according to the Standard. On layers where more than 6 specimens where obtained, the exceeding ones were used for models validation. Fully reversed $R = -1$ LCF tests were run in mechanical strain control, with a testing frequency of 5 Hz. Different values of total strain amplitude were chosen for each layer. The testing machine is an INSTRON 8801 Fatigue Testing System equipped with a load cell of 100 KN, and hydraulic grips. Hardness measurements were obtained by means of a Galileo A 200 durometer. Each reported hardness result is the average of 3 measurements.

4. Experimental results

In Table 1 the average grain dimensions for different cylinder head cut layers are reported. Monotonic tensile characterizations allowed obtaining the average mechanical properties (Fig. 2 (a) and (b) as examples). The whole experimental LCF plan is reported in Table 1 along with the corresponding test results. Plastic strain amplitude is calculated as the difference between mechanical and elastic strain amplitudes, with the elastic strain calculated as the ratio between the corresponding stress and the elastic modulus obtained from the monotonic static tests.
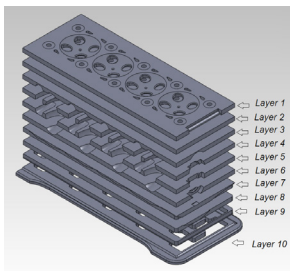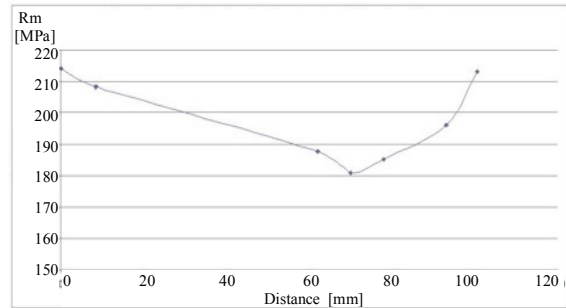

Fig. 1. Cylinder head cutting layout

Fig. 2. UTS testing results at different layers

Table 1. Experimental results.

Layer	Specimens	$\Delta\varepsilon_{mech}$ [%]	$\Delta\varepsilon_{pl}$ [%]	N_f	Average grain size [µm]	Distance from gas face [mm]
1	1_1÷1_6	0.44÷0.64	0.025÷0.141	80÷12905	60	0
2	2_1÷2_8	0.05÷0.08	0.007÷0.024	212÷30498	80	8.5
3	3_1÷3_6	0.05÷0.07	0.007÷0.024	263÷9750	-	22
6	6_1÷6_4	0.05÷0.08	0.007÷0.024	441÷15500	130	62
7	7_1÷7_9	0.30÷0.49	0.016÷0.054	415÷14032	150	70
8	8_1÷8_6	0.05÷0.082	0.007÷0.021	393÷7000	120	78
9	9_1÷9_9	0.09÷0.59	0.017÷0.114	1207÷26376	110	93
10	10_1÷10_5	0.05÷0.12	0.018÷0.052	32÷11827	90	100

5. Damage models application

   For what concerns the BMC model calibration and validation, according to the Standard ASTM E739, a linear regression of data in a double logarithmic scale graphs is performed. The relation between plastic strain and number of reversals to failure is described as reported in Eq. (1), and it can be equivalently rewritten as:

$$N_f = \left(\frac{\Delta\varepsilon_{pl}}{\varepsilon'_f} \right)^{1/c} \tag{5}$$

   From experimental data regression, the fatigue ductility coefficient and the fatigue ductility exponent can be computed. In Table 2, a summary of the calibration parameters is reported. The results are showed in Fig. 3 (a) and (b), related to layer 3 and 7 respectively, which are the best and worst fitting, according to the corresponding determination coefficient. The material parameters show a trend comparable with other mechanical properties related to the distance from the gas face of the cylinder head. The results related to the MC model validation are reported in Table 3. The percent difference between the predicted number of cycles to failure and the experimental values related to the LCF life of the AlSi9Cu1 cylinder heads at room temperature ranges between 29% and 83%.

Table 2. MC and ALSE model calibration summary.

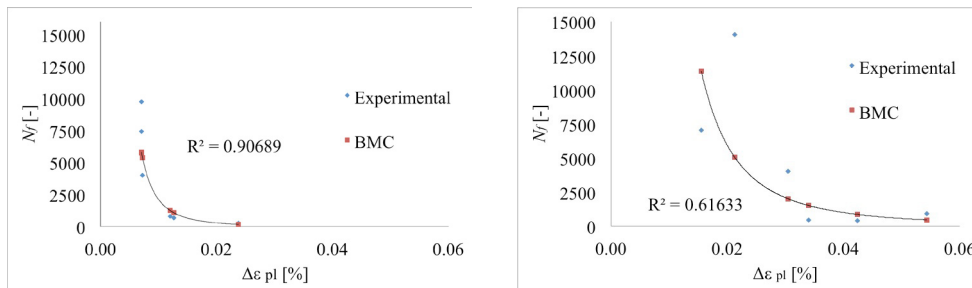| Layer	MC model			ALSE model			
	ε'_f	c	R^2	α	β	R^2	$\overline{\sigma}_{max}$
1	1.159	−0.384	0.75	$5 \cdot 10^6$	41.51	0.90	150
2	0.237	−0.377	0.72	10^7	242.8	0.91	152
3	0.142	−0.347	0.91	10^6	149.9	0.87	144
6	-	-	-	$4 \cdot 10^6$	179.5	0.80	142
7	0.582	−0.388	0.62	$5 \cdot 10^6$	74.67	0.75	142
8	0.733	−0.566	0.66	$2 \cdot 10^6$	154.4	0.82	131
9	2.816	−0.512	0.89	$4 \cdot 10^6$	26.9	0.90	-
10	-	-	-	$3 \cdot 10^6$	121.4	0.98	141

Fig. 3. Layer 3 (left) and 7 (right) data fitting: experimental calibration data (blue), model fitting curve (black), experimental validation data (red).

   For what concerns the ALSE model calibration and validation, data fitting was performed layer per layer and it was possible to approximate the data trends with a determination coefficient ranging from 0.75 to 0.98, as reported in Table 2. It can also be noted that the life estimation key parameter $\overline{\sigma}_{max}$ appears to be less dependent on material properties rather than to stress conditions. The determination coefficients related to W_{ASLE} parameter model are globally higher with respect to the ones obtained for the BMC calibration, suggesting a better fitting relation between the calibration variables and the experimental data. The results are showed in Fig. 4 for layer 7 and 10, which are the best and worst fitting, according to the corresponding determination coefficient.
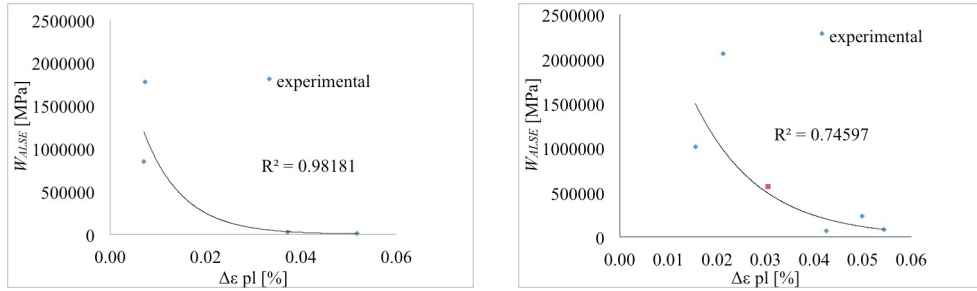
Fig. 4. Layer 10 (left) and 7 (right) data fitting: experimental calibration data (blue), W_{ALSE} fitting curve (black).

To perform the ALSE model validation, the following procedure was followed. According to the parameters of Table 2 and Eq. (3), the empirical parameter W_{ALSE} can be estimated for any layer and any plastic strain value. Reversing Eq. (5), taking into account of Eq. (3), and knowing the value of the equivalent stress for each specimen sample, an estimation of the number of cycle to failure is obtained:

$$N_f = \frac{W_{ALSE}}{\overline{\sigma}_{max}} \qquad (6)$$

Specimens adopted for validation and the corresponding estimated parameters are reported in Table 3 along with results; the estimated numbers of cycles are reported with the percent difference with the experimental results. In Figures 5 and 6 the same results are plotted.

Table 3. ALSE and MC models validation results.

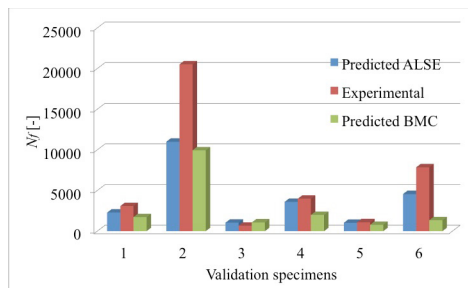| Specimens	Experimental N_f	ALSE N_f	ALSE Difference [%]	BMC N_f	BMC Difference [%]
1_1	3088	3248	5.2	1726	−44.1
2_1	20516	11004	−46.4	9949	−51.5
3_5	681	1049	54	1080	58.6
7_6	4000	3607	−9.8	1995	−50.1
8_5	1102	1032	−6.4	780	−29.2
9_6	7853	4568	−41.8	1345	−82.9

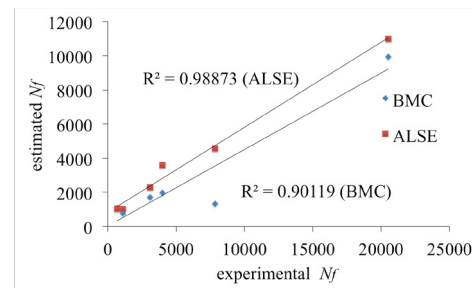Fig. 5. Comparison of life estimations for ALSE and BMC models.

Fig. 6: Experimental TMF life versus predicted fatigue life.

6. Discussion and conclusions

In the present analysis two LCF models were calibrated and implemented with specimens obtained from different layer of a commercial Aluminium alloy cylinder head. The comparison between the estimated life cycle shows that, in isothermal conditions, the estimation obtained by means of a new energetic model are closer to the actual specimens duration than BMC estimations. The BMC model, according to Standard, follows the experimental

data with a power law with determination coefficients lower than those of the ALSE model, which follows the data with an exponential law of better approximation. To properly estimate the residual life of actual components, the ALSE model needs the parameter $\overline{\sigma_{max}}$, i.e. the story of the maximum stress over the loading cycles. Either the highest equivalent uniaxial strain value in the model, or just the highest strain value of the whole strain field, could be employed to estimate the W_{ALSE} parameter, depending on which is the highest between the two. By means of the maximum stress history, an estimation of the number of cycles to failure can be obtained. Finally, the life prediction capabilities of the ALSE model show lower differences with experimental number of cycle to failure than those of the BMC model. This can be considered a promising result for a new life model that has to be further developed.

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