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On the Service Life Prediction of Diesel Engine Cylinder Head under Thermo-mechanical Fatigue Loading with Several Damage Models: A Comparative Study

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The objective of the present paper is to assess the capability of several classical damage models in prediction of service lifetime of engine components subjected to Thermo-mechanical Fatigue (TMF) loading. The focus of the present study is based on efficient and robust predictive tools which are suitable in industrial development process, thus the classical fatigue damage models are selected to perform such a task. In the classical framework, three strain-based models including Manson-Coffin, Smith-Watson-Topper and Ostergren models and one plastic strain energy-based model are examined. Besides, some correction factors are added to the Manson-Coffin, Ostergren and plastic strain energy models regarding the mean stress and temperature effects. The statistical analysis of the models is carried out utilizing the Low-cycle Fatigue and Thermo-mechanical Fatigue tests on standard specimens of A356 aluminum alloy taken from the literature. The analysis indicated that the modified Ostergren model is the most reliable model in fatigue lifetime estimation of the A356 alloy among the others. The studied engine component is a passenger-car diesel engine cylinder head made of A356 aluminum alloy. The temperature, stress and strain distribution fields of the component are considered as the given boundary conditions from our previous work as they are not in the scope of the present investigation. The selected damage models based on the best accuracy identified during statistical analysis are introduced into the ABAQUS software. The results confirmed the statistical analysis results. The modified Ostergren model presented the most accurate and realistic results based on empirical observations of fatigue crack area in diesel engine cylinder heads studied in the literature.

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1. Introduction

Nowadays, vehicles and particularly internal combustion engines plays an important role in daily life of every person around the world. Safety and reliability concerns and also the customer expectations demand an advanced design process and making a more acceptable balance between cost and service lifetime. On the other hand, the constant increasing of the rigorous environmental and economical restrictions, in turn, put the engine parts under more severe mechanical and thermal loads. Such circumstances are more significant in fatigue-critical parts which subject them to risks of failure by Thermo-mechanical Fatigue (TMF) [1,2].

In the past decades, many calculation methods and test protocols have been developed in order to estimate the service lifetime of engine components subjected to thermo-mechanical loadings. The main focus of such developments is to improvement of the constitutive models and damage criteria which are responsible for description of materials behavior [2]. constitutive material model determines the thermo-mechanical response of the component resulting in generating a cyclic hysteresis stress-strain history. Based on this response, the lifetime can be estimated by means of a suitable damage model. The models should be applicable in an industrial context regarding the time and computational effort [2, 3].

Due to aforementioned restrictions, the two-layer visco-plastic constitutive model [4] has commonly employed for modeling the fatigue response of materials and components [4-9]. It is suitable for modeling materials exhibiting visco-plastic behaviors which is typically appears by metals at elevated temperatures. It is efficient, simple to use and available in ABAQUS FEM package [10].

The main mechanism affecting the TMF lifetime is the accumulation of damage during cyclic plastic deformation. The main challenge in this research area is to describe the complex interactions of different damage mechanisms. In particular, for the metallic components at high temperatures, the dominant damage mechanisms have been known as fatigue, oxidation and creep [11]. There are several fatigue lifetime estimation models considering one, two or all of the mentioned damage mechanisms in metals.

There are two categories of damage criteria proposed until now. The parametric lifetime models which are mainly based on parameters of the stabilized hysteresis loop. It is assumed that the discrete evolution of damage from cycle to another cycle is controlled by the respective macroscopic parameters of the stabilized cycle. Therefore, there are several families of parametric models based on the representative integral parameter such as, stress-based, strain-based and energy-based models [11]. Another class of lifetime model entitled "incremental lifetime models" in which a continuum evolution of damage during each cycle has been hypothesized. The aforementioned evolution is formulated as an additional differential equation with respect to the internal variable for damage. The advantage of incremental lifetime models is that they can deal with any arbitrary and complex loading histories and multiaxial loadings, however this class of lifetime models demands higher computational effort caused by integration procedure during their usage [11]. In the incremental lifetime models, the fatigue lifetime has been considered to be the inverse of damage increment during the stabilized cycle. For calculation of damage increment, several formulations have been presented, taking the damage accumulation rate as a function of flow rate [12-14] and those formulations in which the effect of creep has been highlighted in them [15, 16].

Among the most common incremental models, the Chaboche-Lemaitre creep-fatigue lifetime model [17] was used in order to TMF lifetime prediction of engine Exhaust manifold [18]. Neu and Sehitoglu [19], proposed a sophisticated damage rate model separating each of the fatigue, oxidation and creep damages. This model is available in FEMFAT commercial code and successfully employed in lifetime estimation of several engine parts [8, 9, 20]. Wu et al [21-22], added the intergranular embrittlement damage mechanism into the damage rate model and the accuracy of such a model in predicting the TMF lifetime of a ductile cast iron was examined. Despite the good

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accuracy of such models in fatigue description of materials, applying them to complex structures has been rare due to a time-consuming computational effort.

Contrary to incremental lifetime models by which accounts explicitly for different damage mechanisms throughout damage laws, the parametric models account for related mechanisms implicitly by considering a macroscopic parameter that is representative of damage in the material. Among the different categories of parametric models, the stress-based models were presented mainly applicable in high cycle fatigue (HCF) regime but some investigations demonstrated the validity of these models also for the stress-controlled low-cycle fatigue (LCF) applications [23-25]. The most common stress-based model is the Basquine model [26] which relates the stress amplitude with the fatigue lifetime in a logarithmic scale. Later, some modifications on this model were made mainly by consideration of the effect of mean stress parameter on the fatigue lifetime like Goodman [27] and Soderberg [28] models.

The strain-based models generally presented for strain-controlled LCF conditions. It relies on the Manson-Coffin [29-30] equation which describes the linear relation between plastic strain amplitude and fatigue lifetime in a logarithmic scale. With combining of the Manson-Coffin relation with the Basquine’s one, the total strain approach of Manson-Coffin-Basquine has been presented which is the simplest and most common approach in the fatigue field. The effect of various loading parameters on strain-based lifetime models was examined like the influence of mean stress by Morrow [31] and Smith-Watson-Topper [32] and the influence of frequency effect by Ostergren [33]. The disadvantage of these models is the consideration of material constants at a constant loading condition such as constant temperature or the strain rate during fatigue tests which restricts their applications to varying conditions like TMF.

Another category of parametric models, the energy-based models, correlates the fatigue lives with hysteresis strain energy dissipated during the stabilized cycle called plastic strain energy density. Skelton [34] suggested that the plastic strain energy density expresses the necessary energy for propagation of fatigue crack. It was observed on some parts under investigation that the fatigue damage is still active in the material even though the deformation is pure elastic. Such an observation of demanded the consideration of the tensile elastic strain energy in the energy-based models [35-36]. Later, the effect of mean stress on fatigue lifetime was considered in the energy-based models. Gocmez et al [37] added a stress correction factor to the plastic strain energy model accounting for the effect of mean stress and maximum stress on the fatigue lifetime. Besides, a temperature correction factor was added to the model in order to account for the damage of the material at elevated temperatures. With such a formulation, the elevated temperature damage mechanisms like oxidation and creep was considered in an implicit manner. This formulation was used for the fatigue lifetime prediction of three families of cast irons under LCF and OP-TMF.

An important class of parametric models is the Fracture Mechanics approach. This approach states that a large part of the fatigue lifetime of the material is related to processes during which microcracks initiate and develop until some macroscopic crack initiates. After this stage, crack propagation starts and usually taken into account throughout the Fracture Mechanics analysis. This approach is suited for those situations when the component fatigue lifetime is dominated by the propagation of the microcracks and not their incubation stage. Regarding the fracture mechanics approach, Tomkins et al [38] considered the effects of the crack propagation and the crack closure in their model. A model for the TMF lifetime estimation based on a crack growth law considering the cyclic crack-tip opening displacement was presented by Seifert et al. [39-40] and successfully applied to cast iron materials.

Cylinder heads are the most critical components subjected to thermo-mechanical loadings induced by start-up and shut-down cycles of the engine. Such loading cycles put the cylinder head on transient temperature distributions. The correct prediction of

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temperature distribution is highly crucial in fatigue lifetime estimation procedure however, it is not in the scope of the present research, then the temperature field has been taken from our previous work.

In the fatigue estimation process of a component, a stabilized state of the material would be considered which will be achieved after some loading cycles. Typically, at about 10% of the overall lifetime of the component subjected to TMF, the first micro-cracks could be observable. Thus, in order to define a failure criterion for the component, an allowable crack length has to be defined which can be considered as macroscopic crack onset for typical applications [7]. The fatigue lifetime of the component ends up with the appearance of the technical crack(s) with the order of size of few millimeters. These technical cracks originate from growth and coalescence of the microcracks which generally initiate under cyclic loading on the site of material imperfections [41, 42].

In this paper, different damage criteria in order to estimate the TMF service life-cycle of an engine component have been studied. For the sake of application of the model in an industrial development process, the focus has been put on efficient and robust damage models demanding minimum computational effort with high accuracy. Therefore, several models have been examined to identify the most suitable model for this purpose. Despite the fact that the fracture mechanics approach and incremental damage models present a high accuracy in description of materials fatigue performance, they are not computationally conservative. Besides the fracture mechanics concept needs the introduction of an initial crack or flaw into the model before the analysis. Such a task is not reasonable in an industrial context. Thus, several classical models have been examined and compared. The best classical models identified in statistical analysis stage have been applied to service life prediction of a passenger-car diesel engine cylinder head under TMF loading and the capability of them to detect the most probable fatigue crack area and its corresponding fatigue lifetime has been discussed.

2. Damage Criterion

As mentioned in the introduction, the main focus of this investigation is to identify a robust phenomenological law in order to estimate the fatigue lifetime of an engineering component. For the sake of efficient use in the industrial development process, the classical models are preferable. Therefore, a number of most common classical models in the field of LCF/TMF including strain-based and energy-based models are considered and their advantageous and disadvantageous are discussed.

The classical fatigue damage models could be described in a general power law form as follows [37]:

$$N_f = A(P)^{-B} \quad (1)$$

Where N_f is the number of cycles to failure, P is the damage parameter and A and B are two material constants determined by a regression approach. such a formulation describes the inverse relation between the fatigue lifetime and damage parameter. The damage parameter is expressed regarding the damage model considered. Four common classical damage models considered in this study are presented in Table 1.

The first damage model considered is the simple Manson-Coffin law [30, 31] that introduces the plastic strain amplitude of the stabilized cycle as the damage parameter. Since the Manson-Coffin law was unable to specify the mean stress effect on fatigue lifetime, Smith et al. [32] proposed a damage model which included the mean stress effect into account thorough the consideration of maximum stress and total strain range. This model is commonly known as Smith-Watson-Topper damage model. Ostergren [33] applied the frequency effect in the classical approach through a multiplication of maximum stress and plastic strain range. The last model is an energy- based model in which introduces the plastic strain energy per cycle as the damage parameter which is equal to the area of the stabilized hysteresis loop as the following [43]:

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$$\Delta W = \oint \sigma d\varepsilon = \int_{cycle} \sigma d\varepsilon \approx \Delta\sigma\Delta\varepsilon_p \qquad (2)$$

Since integration from the stress-strain hysteresis loop demands a time-consuming process and not applicable in industrial context, the value of the plastic strain energy density has been approximated as the product of the plastic strain range and the stress range [43].

Table 1: the studied damage models in the present investigation

Damage Model	Damage Parameter
Manson-Coffin	$P_{MC} = \varepsilon_{a,p}$
Smith-Watson-Topper	$P_{SWT} = \sqrt{E(T)\sigma_{max}\Delta\varepsilon_t}$
Ostergren	$P_{OST} = \sigma_{max}\Delta\varepsilon_p$
Plastic strain energy	$P_{PSE} = \Delta W$

As it was mentioned in introduction, classical models like The Manson- Coffin damage criterion are not able to capture the temperature effect adequately. As will be shown in the next section, when LCF tests for only one temperature were considered for the regression analysis, much better accuracy resulted. This implies the temperature dependency of the material constants of the Manson-coffin law by which restricts its application to only constant temperature applications like LCF. In order to overcome this difficulty and make the Manson-Coffin law applicable for TMF conditions, Ohmenhauser et al. [7] proposed an enhanced Manson-Coffin law by defining a temperature dependent damage parameter as the following:

$$N_f = A.P_{MC}(T)^{-B} \qquad (3)$$

Where $P_{MC}(T)$ has been defined as:

$$P_{MC}(T) = \frac{\varepsilon_{a,p}}{\sqrt[B]{d(T)}} \qquad (4)$$

Gocmez et al. [37] modified the classical plastic strain energy model by two correction factors in order to enhance the model capability for LCF/TMF description. They added a stress correction factor accounting for the effects of mean stress and a temperature correction factor in order to account for the damage mechanisms in the material at high temperatures into the model. With such a formulation, the elevated temperature damage mechanisms including oxidation and creep were considered in the lifetime model in an implicit manner. Although the model indicated an enhanced accuracy for three different cast iron families, Farrahi et al. [43] questioned the model capability in the case of aluminum alloys. Thus, they improved the model accuracy by modifying the stress correction term. Based on the work of Farrahi et al. [43], the temperature correction term would be as the following form similar to Gocmez et al. [37]:

$$\varphi_T = \left[\frac{exp\left(-\frac{T_{act}}{T_{max}}\right)}{exp\left(-\frac{T_{act}}{T_m}\right)}\right]^n \qquad (5)$$

Where n is a material constant, T_{max} is the maximum temperature, T_m as the melting temperature and T_{act} is the activation temperature which has been assumed that above the activation temperature, the creep and oxidation mechanisms start to operate. The value of activation temperature has been selected to be 42.5% of the melting temperature of the material [43].

The mean stress correction term has been defined as the following form [43]:

$$\psi_\sigma = \left(1 + m_1 \frac{\sigma_{mean}}{\sigma_a}\right)^{m_2} \qquad (6)$$

In which m_1 and m_2 are material constants.

The corrected plastic strain energy model according to Farrahi et al. [43] would be in the following form:

$$N_f = A[\Delta W(\varphi_T + \psi_\sigma)]^{-B} \qquad (7)$$

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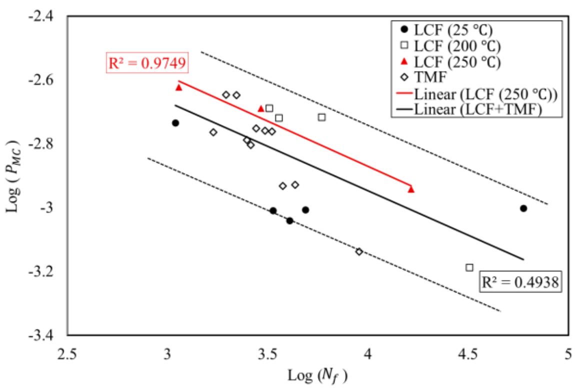
Pan et al. [44] added the mean stress effect into the Ostergren damage model by a stress correction factor. The modified Ostergren damage parameter is as follows [44]:

$$P_{OST} = \sigma_{max}\Delta\varepsilon_p \left[1 + \frac{\sigma_{mean}}{\sigma_{max}}\right]^n \qquad (8)$$

Where *n* is a material constant.

3. Statistical analysis

In order to determine the material constants of the models, a regression analysis of the experimental lives determined in the LCF and TMF experiments in a logarithmic scale is performed. The statistical coefficient of determination (CD) provides a measure for the reliability of the model. If it was equal to one, it means that the model has been completely fitted to the experimental data.



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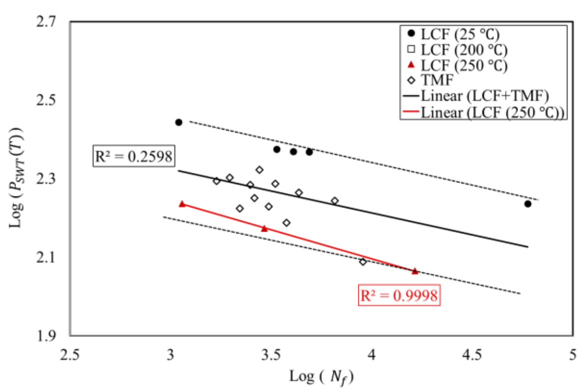

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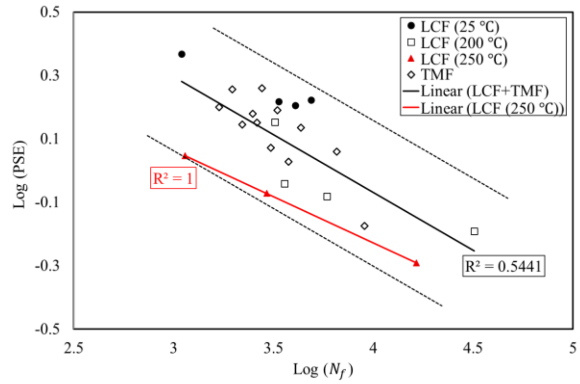

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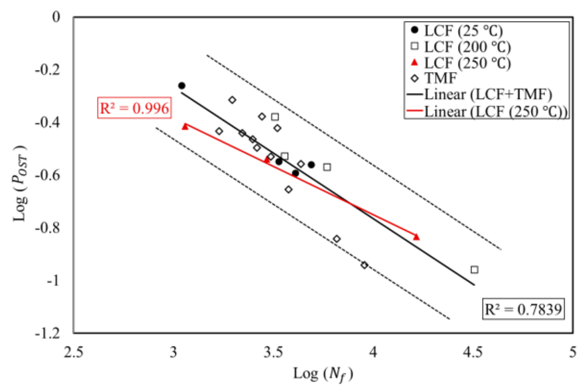

(d)

Figure 1: Regression analysis of (a) MC (b) SWT (c) PSE and (d) OST models using experimental data of A356 alloy

The examined material in this study is a typical cast aluminum-silicon alloy which has been widely used in diesel engine cylinder heads. In order to evaluate the lifetime models, LCF and OP-TMF tests on the standard A356 aluminum samples from the literature [45] were utilized. The LCF tests have been done at three temperatures of 25 ℃, 200 ℃ and 250 ℃ and also different strain amplitudes in the range of 0.2-0.35 %. The TMF tests were at minimum temperature of 50 ℃ and different maximum temperatures between 200-250 ℃. The mentioned loading conditions had been chosen based on working conditions in passenger-car diesel engine cylinder heads. More details about the test facilities and loading conditions could be found in the literature [45].

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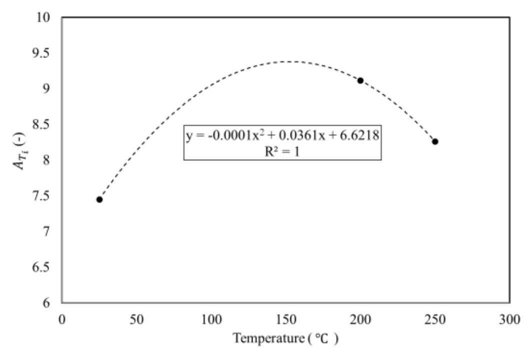
The statistical analysis of four classical models including Manson-Coffin (MC), Smith-Watson-Topper (SWT), Plastic strain energy density (PSE) and Ostergren (OST) models utilizing LCF/TMF experimental data of A356 aluminum alloy are depicted in Figure 1. For this purpose, the related damage parameters of the models are plotted against experimental fatigue lives in a logarithmic scale and then the linear regression function fitted to the data following the least-squares approach. Besides, two most common statistical parameters including the Coefficient of determination (CD) and Average of relative Errors (ARE) for the examined models are reported in Table 2.

Table 2: The Coefficient of Determination (CD) and Average of Relative Errors (ARE) determined in regression analysis of damage models

Damage Model	CD	ARE (%)
Manson-Coffin	0.4938	52.1487
Smith-Watson-Topper	0.2598	58.7187
Plastic Strain Energy	0.5441	42.9525
Ostergren	0.7839	30.1673
Enhanced Manson-Coffin	0.5194	33.0443
Corrected Plastic Strain Energy	0.6188	38.6367
Corrected Ostergren	**0.7993**	**29.0299**

As it could be seen in Table 2, the Ostergren model has the highest accuracy among the others and the lowest accuracy is related to the Smith-Watson-Topper damage model. It is worth noting that all of the classical models except the PSE, have temperature dependent material constants which restricts their application to only constant temperature conditions like LCF. It is because of that the material parameters should be determined in a constant condition, e.g. constant temperature or constant loading rate. the SWT model has some degrees of temperature independency since the elastic modulus in its formulation could be introduce the temperature effect through the influence of temperature on Young's modulus. In the case of PSE model, it was reported [43] that this model can describe the temperature influence on fatigue lifetime adequately with consideration of one set of material constants.

On the other hand, a tricky way to apply the temperature dependent damage models to TMF conditions is to determine the material constants at maximum temperature available in the experimental data noting to the maximum temperature that the component experiences during service. Therefore, the regression analysis of the aforementioned models is also conducted under maximum temperature in the LCF data. As it could be observed in Figure 1, the CD parameter takes a very good value. The highest CD parameter is related to PSE and OST models; thus, these two models will be examined in the component level.



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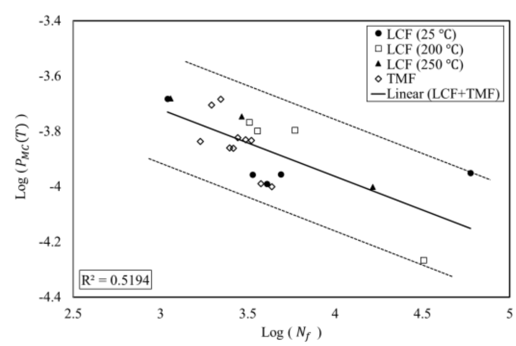

(b)

Figure 2: (a) Determination of the normalizing temperature function in the enhanced MC model and (b) Regression analysis of the enhanced MC model

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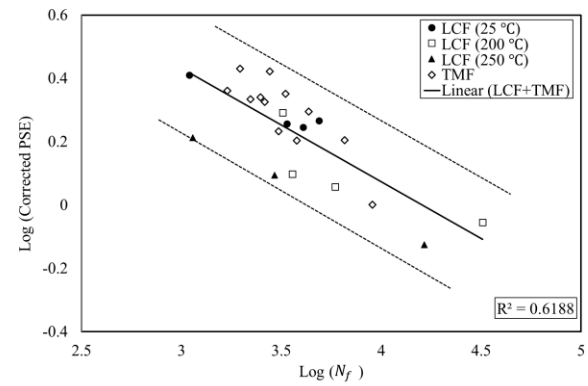
As it was stated in the previous section, a temperature correction function added to the MC model to improve the description of temperature influence. In order to determine the temperature correction function *d(T)*, the values of the constant *A* are determined for each temperature in LCF tests using the regression analysis at each temperature. The correction function *d(T)* is then determined as a suitable fitting function of these individual values A_{Ti}. The chosen function according to Figure 2 (a) has three independent parameters determined by regression analysis. In the second step, the parameters *A* and *B* are determined utilizing the regression analysis involving all LCF and TMF data provided [7].

In order to choose the temperature value associated with the TMF tests, theoretical and practical aspects have been presented. theoretical point of view defines a weighted average temperature. practical approach is on simply use the maximum temperature within the TMF cycle. It has been proved that using the practical approach, better statistical reliability could be achieved and therefore the practical approach has been considered in this paper [7].

The statistical examination of the enhanced MC model is depicted in Figure 2 (b). From the figure it could be claimed that the MC model reliability has been enhanced but the amount of enhancement is not significant.

Following the explanations in the previous section, two temperature and mean stress correction factors added to the PSE model. Besides, a mean stress correction factor also added to the OST model to improve the reliability of the models. The regression analysis of these two corrected models have been depicted in Figure 3. As it could be observed in the Figure and also statistical parameters reported in Table 2, the fatigue description of both PSE and OST models has been improved by adding the mean stress/temperature effects, however the amount of improvement of fatigue description in the OST model is not so significant.



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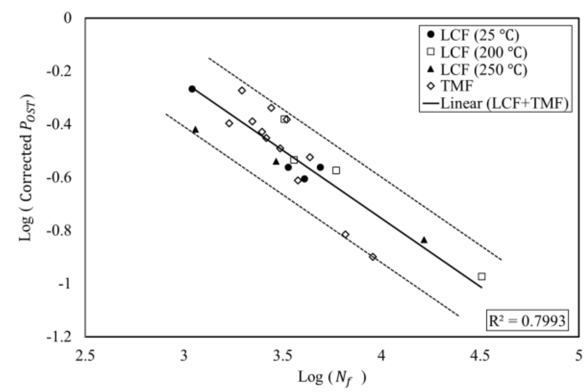

(b)

Figure 3: Regression analysis of the (a) corrected PSE model and (b) modified OST model

As an overall conclusion based on statistical analysis results, the damage models could be arranged in terms of fatigue description capability as follows:

Corrected OST > OST > Corrected PSE > PSE > Enhanced MC > MC > SWT

The OST model with the mean stress correction factor term presents the highest reliability among the others and also has the lowest width of scatter-band according to Figure 3 (b).

In the next section, the OST and PSE models and also their corrected versions will be examined at TMF lifetime prediction of a diesel engine cylinder head. Also, the OST and PSE models calibrated by LCF tests at maximum temperature will be examined to assess the

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reliability of the approach of determining the material constants at maximum temperature.

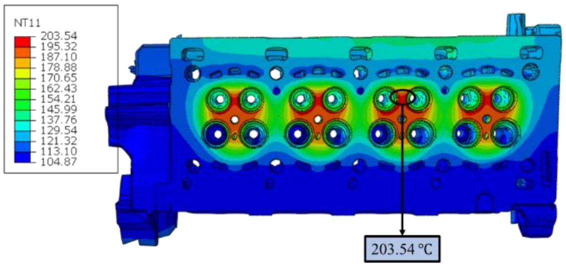


Figure 4: the temperature distribution in the cylinder head at full throttle condition [45]

4. Finite element implementation

The studied component in this paper is a passenger-car diesel engine cylinder head made of A356-T6 aluminum alloy. After preparing the CAD file and meshing, the CFD and Gas dynamics analysis have been conducted in order to pass the necessary information needed for heat transfer analysis. These actions are not in the scope of the present paper and therefore the temperature distribution has been considered as a given boundary condition [45]. The temperature distribution of the aluminum cylinder head at full throttle condition could be observed in Figure 4 where the maximum temperature has been detected in a site between the gas ports in cylinder No. 2. The value of maximum temperature agreed with temperature survey data [45]. Considering the melting temperature of 585 ℃ for A356 aluminum alloy, with such a temperature in cylinder head, the presence of viscous effects is inevitable.

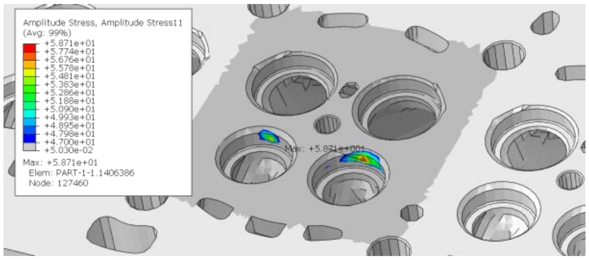
The Two-layer visco-plastic constitutive model available in ABAQUS software has been adapted to predict the stress and strain field in the structural level. Only two cycles of TMF has been considered. A TMF cycle has been defined as a start-up of the engine (thermal load) and shut-down (cooling), all followed by a residual stress level including the bolt pre-tension forces and fitting of valve seats and valve guides. Since in the industrial development stage, few cycles could be loaded on the component due to computational concerns, therefore the cyclic hardening/softening could not be simulated well and thus applying two TMF cycles seems un-necessary. More details about the structural and constitutive simulations of the present cylinder head are reported in our previous work [8]. Since the two-layer visco-plastic constitutive model distinguishes between plastic and viscous strains, a more suitable notation is based on the quantity of inelastic strain ε_{in} instead of plastic strain ε_p to use in the damage models.

It is important to point out that all of the considered damage models are presented originally for uniaxial loading conditions. Extending them to multiaxial case needs the employment of critical plane approaches or equivalent form of stresses and strains. There are different critical plane theories available until now to perform such a task that a review on them is not in the scope of the present paper and could be found elsewhere [46]. For the sake of simplicity, the maximum principal stress and equivalent plastic strain are considered for multiaxial fatigue analysis [8].

All the damage models are programmed in ABAQUS software as a post-processor PYTHON script. The input quantities are extracted from the two last steps of loading including combustion pressure in cylinder No. 2 and cooling steps. The distribution of logarithmic fatigue lifetime could be extracted from the developed code and observed as a contour plot in a standard post-processor software like ABAQUS/Viewer.

5. Results

In Figure 5, the distribution of amplitude stress and mean stress in the fire deck of cylinder No. 2 could be observed. As it could be seen, the highest stress amplitude and mean stress of a TMF cycle in the diesel engine cylinder head is accommodated on gas port seat area. Therefore, it could be expected that the macroscopic crack initiation site would be the region around the same maximum site as stress amplitude and mean stress.



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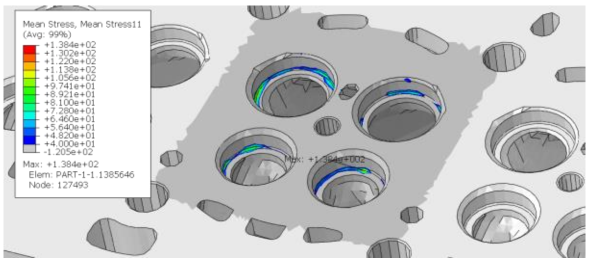


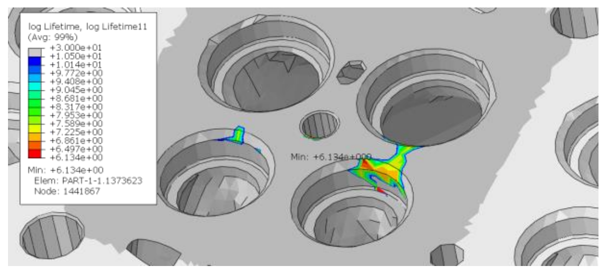
(b)

Figure 5: the distribution of (a) stress amplitude and (b) mean stress in the fire deck of cylinder No. 2

The field distribution of fatigue lifetime in the flame deck of cylinder No. 2 estimated by PSE and Corrected PSE models are depicted in Figure 6 (a) and (b), respectively. Also, the node corresponding to failure site and its corresponding fatigue lifetime estimated by the examined models are reported in Table 3. Although both PSE and corrected PSE models indicate one single node accommodated on valve port as the failure site, the value of fatigue lifetime in the corrected PSE model has been considerably improved and has become more realistic. Such a significant reduction in fatigue lifetime with adding correction factors to the PSE model shows the important role of temperature and mean stress in cylinder head cyclic service.

The field distribution of fatigue lifetime in the flame deck of cylinder No. 2 estimated by OST and corrected OST models are depicted in Figure 7 (a) and (b) respectively. Similar to statistical analysis of these two models, the fatigue lifetime of the cylinder head was more realistic with consideration of mean stress correction factor in OST model but the improvement was not significant. Comparing with the energy-based model, the location of fatigue crack predicted by OST model has more agreement with experimental observations.

The field distribution of fatigue lifetime in the flame deck of cylinder No. 2 estimated by OST and corrected OST models are depicted in Figure 7 (a) and (b), respectively. Similar to statistical analysis of these two models, the fatigue lifetime of the cylinder head was more realistic with consideration of mean stress correction factor in OST model but the improvement was not significant. Comparing with the energy-based model, the location of fatigue crack predicted by OST model has more agreement with experimental observations.



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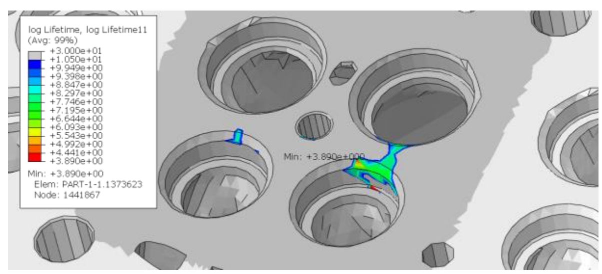

(b)

Figure 6: The distribution of fatigue lifetime in fire deck of cylinder No. 2 estimated by (a) PSE and (b) corrected PSE models

The field distribution of fatigue lifetime in the fire deck of cylinder No. 2 estimated by PSE and OST models calibrated with LCF tests at maximum temperature are depicted in Figure 8 (a) and (b) respectively. The predicted location of failure was similar to OST model and also the experimental observations, however the value of estimated fatigue lifetime was not reasonable.

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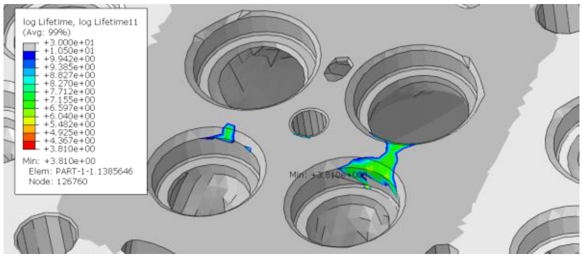
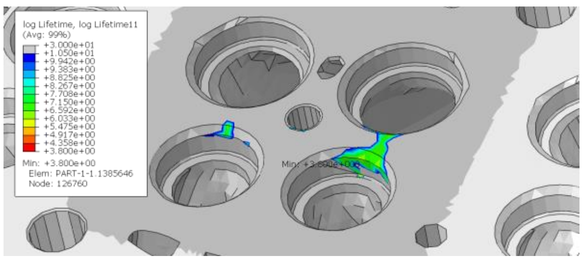
Therefore, the approach of calibration of damage models using maximum temperature LCF data is rejected.



(a)



(b)

Figure 7: The distribution of fatigue lifetime in flame deck of cylinder No. 2 estimated by (a) OST and (b) corrected OST models

Table 3: the failure site and fatigue lifetime predicted by the examined models

Damage Model	Node	Lifetime (Cycles)
PSE	1441867	1361445
Corrected PSE	1441867	7763
OST	126760	6457
Corrected OST	**126760**	**6309**
OST (calibrated at Max temperature)	126760	152405
PSE (calibrated at Max temperature)	126760	149968

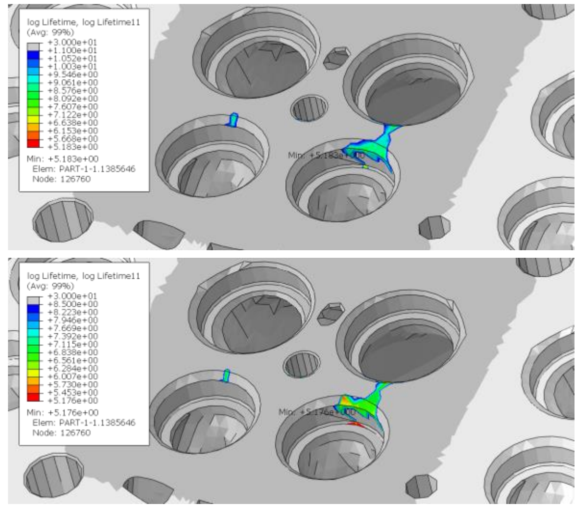
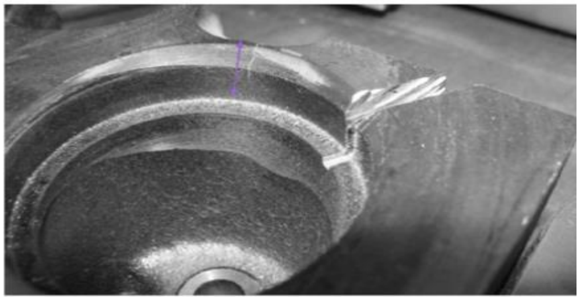


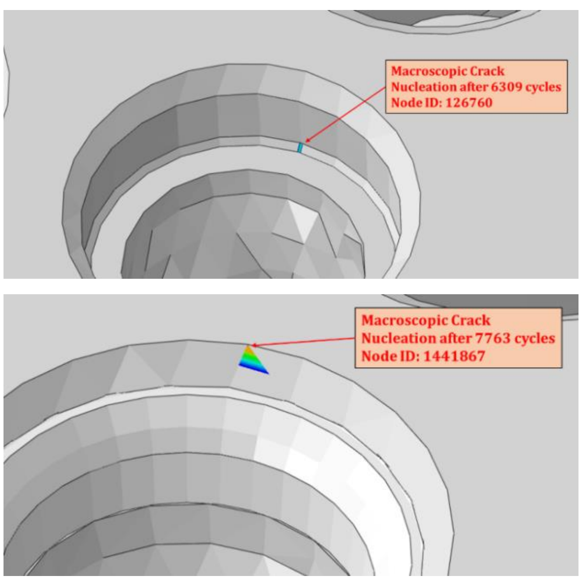
Figure 8: The distribution of fatigue lifetime in flame deck of cylinder No. 2 estimated by (a) PSE and (b) OST models calibrated using LCF data at maximum temperature

Figure 9 presents the comparison of the results of corrected PSE and corrected OST models with real diesel engine cylinder heads failed during service from the literature [47, 48]. Experimental evidence indicates that the most probable crack initiation site is on the gas port's valve seat and the gas-air valve bridge. Such observations are in agreement with mean stress distributions (figure 5 (b)) in which introduces the port seat as a highly potential site for macroscopic fatigue crack initiation. The positive role of mean stress correction factor in improvement of the reliability of corrected PSE and corrected OST models originates from this argument. The failure location predicted by OST model is in more agreement than PSE model. Regarding the number of cycles to failure, there are no available results of thermal shock test for the present cylinder head to compare and assess the models. Nevertheless, considering the simplifications and hypothesis that are made during the development process of component, it is reasonable to trust to the model with lowest predicted values of fatigue lifetime. Therefore, it could be claimed that the Ostergren damage model with a mean stress correction factor provides the most reliable results for TMF lifetime prediction of engine components among the classical models. Besides, the simplicity and efficient use of this model is it’s another advantage in comparison to complex models like incremental and fracture mechanic approach.



(a)

(b)



(c)

Figure 9: (a) Experimentally detected [47, 48] and predicted site by (b) corrected PSE and (c) corrected OST models of crack initiation site in diesel engine cylinder head

6. Conclusions

The fatigue lifetime prediction of a diesel engine cylinder head made of cast A356 aluminum alloy was carried out using several classical damage models. The models including Manson-Coffin (MC), Smith-Watson-Topper (SWT), plastic strain energy (PSE) and Ostergren (OST) were calibrated utilizing a statistical analysis of LCF and TMF experimental data on A356 alloy from the literature. Besides, some correction factors based on temperature and mean stress effect were adapted to the MC, PSE and OST models by which improved the fatigue description capability of the mentioned models. The statistical analysis indicated that the modified OST model presents the best reliability in fatigue lifetime estimation among the other models. Moreover, the PSE and OST models were calibrated by maximum temperature LCF data to examine such an approach in order to TMF description. Then, the corrected and un-corrected PSE and OST models were applied to TMF lifetime estimation procedure of a diesel engine cylinder head. The temperature and stress-strain field distributions were considered as a given boundary condition from the literature. Comparison of Results of simulations and experimental observations of fatigue crack location and lifetime cycle, showed that the corrected OST model presents the most consistent results with experimental observation which in addition to simplicity and efficient use, makes it a suitable damage criterion for development of thermomechanically loaded parts. Since this model in a kind of a statistical approach, it is quite independent of the individual characteristics of different materials and components and therefore is applicable to every kind of metallic materials and components under LCF and TMF loading.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interests with respect to the research, authorship, and/or publication of this article.

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