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Evaluation of Fatigue, Oxidation and Creep Damages on Thermo-mechanical Fatigue Life for Cylinder Heads

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ABSTRACT: The objective of the present study was to analyze the cylinder heads' thermo-mechanical fatigue life. This investigation was done by employing the finite element method. Moreover, ANSYS software was also used to achieve temperature and stress predictions. The thermo-mechanical fatigue life was then examined using Sehitoglu theory and FEMFAT software. The cylinder head's elastic and plastic properties were acquired at various temperatures by low-cycle fatigue tests. Low-cycle fatigue tests were simulated by ANSYS software, and excellent agreement was observed between the experimental and simulation results low-cycle fatigue tests. According to the finite element analysis, 208.6°C and 89.475 MPa were the maximum temperatures and stresses in the cylinder head at the valve bridge, which is located betwixt exhaust valves. The thermo-mechanical fatigue life analysis showed 71.16%, 25.04%, and 3.79% for mechanical, oxidation, and creep damages, respectively. The thermo-mechanical fatigue results proved the significant impact of the mechanical damage on the cylinder head's total thermo-mechanical fatigue life. Moreover, the numerical results indicated the negligibility of the creep damage.

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1- Introduction

In recent years, the growing demand for higher power, lower pollution, and optimum fuel consumption has imposed tremendous limitations on designing the components of internal combustion engines [1, 2]. The cylinder head is one of the crucial engine components that endures various mechanical and thermal loadings. This exposure results from varied and fluctuating temperatures when the engine starts and shuts down. Designing a durable cylinder head that resists lengthy fatigue life is one of the main goals of the design. Mechanically, the cylinder head should be adequately strong in high temperatures to tolerate the alternating stresses of gas heat and pressure since this crucial component is subjected to out-of-phase thermo-mechanical fatigue. Notably, such fatigue is regarded as a major element in cylinder head failure [3, 4, 5]. In other words, shutting the engine down and dropping its temperature to the lowest leads to the cylinder head being subjected to tensile stresses because of the component connectivity. Hence, starting and boosting its temperature enforces the mechanical compressive stresses on the cylinder head. Many of the engineering components encounter failure in their operational conditions under oscillating loading and high temperatures, showing the vital importance of the appropriate prediction of the lifetime of components. Therefore, life prediction models, such as the Sehitoglu model, should be employed to calculate the damage to a material. Regarding mechanical fatigue, oxidation, and creep, this model considers the material damage as a combination of damages [2, 7]. The mechanical fatigue is modeled using classical methods, such as Manson-Coffin-Basquin and strain domain. The oxidation process is regarded as a function of strain domain, strain rate, strain-temperature phase, and oxidation kinetic. Also, the creep damage is based on stress, temperature, strain-temperature phase, and time [8, 9]. Several investigations have been conducted on the cylinder head stress analysis and fatigue life. Hazime et al. predicted the thermo-mechanical fatigue life of cast aluminum cylinder heads regarding the defect distribution. The study confirmed the better correlation of the porosity-based method with experimental engine test results [10]. According to the analysis of Ashouri et al. on the cylinder head's fatigue life, the fatigue of the valve bridge is of low cycle fatigue (LCF) type [11]. Yang and colleagues predicted the cylinder head's fatigue life. Their results, obtained using the Sehitoglu model, verified the foremost impact of mechanical damage on the total life of the cylinder heads [7]. Liu et al. evaluated the thermo-mechanical fatigue life of cylinder heads based on the total damage model. The conducted simulation showed the negligibility of creep damage [2]. Fatigue reliability assessment of engine cylinder heads based on neural networks was done by Jing et al., demonstrating the significant impact of the loading sequence on fatigue reliability evaluation [12].

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Basiri and Amini calculated the cylinder head's LCF regarding various strain criteria. The modified Ostergren model presented the most accurate and realistic results [13]. Ashouri studied the cylinder head's LCF life regarding quenching, and the finite element analysis confirmed the significance of residual stress's impact on LCF life [14]. Ashouri analyzed the thermal stress distribution of a coated cylinder head. The study confirmed that the stress distribution would be declined by using thermal barrier coating [15]. Luo and colleagues performed the finite element analysis-computational fluid dynamics coupled analysis on the thermo-mechanical fatigue of cylinder heads. Their results showed a less than 10% contrast between experimental and simulated results [16]. A software developed by Blondet and Barthoux calculated a total damage map as a result of the failure using finite element analysis [17]. The assessment of the cylinder head lifetime for efficient heavy-duty engines was developed by Hazime et al. The fatigue analysis showed a suitable fit between the predictions and experimental tests [3]. Li and colleagues analyzed the impact of porosity defects on the initiation of the crack in the cylinder head of a diesel engine. The cracks occurred in the intake and exhaust channels and cooling water channels [1]. Chen et al., to improve the high cycle fatigue (HCF) life, performed the cylinder head design process. The minimum HCF life was observed in the water jacket side of the combustion chamber [18]. Mahajan et al. optimized the valve bridge of cylinder heads. The maximum reduction in combustion fatigue margin was about 6% [6]. Wang and colleagues analyzed the low and high cycle life of turbocharged engine cylinder heads, implying the correspondence of the area that showed low cycle fatigue life with the cracking site shown in the experimental tests [5]. Analysis of fatigue crack growth in cylinder head bolts of gasoline engines based on experimental data was done by Akbari and Akbarpour Mamaghani. Numerical results showed that crack existence to a depth of 0.35 mm is the source of failure of premature fracture [20]. Huang et al. established the sub-model method for the structure optimization of cylinder heads. The results showed that the critical area mainly appears in the water jacket [4]. Ashouri predicted HCF for the cylinder head regarding the stress gradient. The study introduced the valve bridge betwixt exhaust valves as the area with the highest temperature and stress occurrence [21]. An experimental study on the ratcheting and fatigue behavior of polyacetal under uniaxial cyclic loading was performed by Shariati et al. The experimental data showed that the ratcheting strain and strain rate ratcheting are sensitive to the applied stress amplitude and the mean stress [22]. The cylindrical shell behaviors (in terms of becoming softened and ratcheted) were explored by Shariati and Hatami, indicating no differences in ratcheting strain for samples during the descending force amplitude [23]. Numerical and experimental investigation of cylindrical shell with cutout under uniaxial cyclic loading was done by Shariati and Hatami. The residual plastic strain was obtained close to the experimental results [24]. Shariati et al. studied the axial cyclic stress-strain characteristics of cylindrical shells. Simulation results showed good agreement between numerical and experimental results [25]. Shariati and colleagues investigated the softening behavior of POM under cyclic strain-controlled loading numerically and experimentally. The investigation demonstrated the considerable impact of increasing strain amplitude on decreasing the fatigue life of specimens [26]. Ashouri explored the cylinder heads' LCF life, showing 1073 cycles as the minimum fatigue life [27].

Various methods and patterns have been presented in different studies to simulate the cylinder head's thermo-mechanical fatigue (TMF) and estimate the fatigue life. The cylinder head would fail because of fatigue, oxidation, and creep damage [2, 7]. As Sehitoglu stated, more profound studies on the different mechanisms affecting the behavior of materials under TMF loading conditions are essential [8, 9]. Diverse studies have been done to investigate the damage of mechanical fatigue in the engine cylinder head. However, the oxidation and creep damages have not been widely explored. Damage parameters of each mechanism are added together to obtain a prediction of total fatigue life. Cylinder head damage comprises mechanical, creep, and oxidation damages. The available literature has mainly explored mechanical damage, while creep and oxidation damages have been excluded due to the Sehitoglu model's extensive parameters, which require expansive tests for their determination. Thus, this study aimed to analyze the thermo-mechanical fatigue of the aluminum cylinder head made of (A356) using the Sehitoglu model to investigate the mechanical, oxidation, and creep damage impacts on its thermo-mechanical fatigue analysis. The present study also examined the cyclic behavior of cylinder head material by conducting LCF tests in various temperatures and calculating kinematic and isotropic hardening parameters in varied temperatures.

2- Methodology

2- 1- The finite element model and material properties

Proper simulation can prevent time-consuming processes and costly designing and reduce the required tests. As a powerful designing tool, the finite element method (FEM) enables the determination of the critical points to predict a component's temperature, stress, and fatigue distribution [28, 29, 30]. Moreover, the component geometric parameters can be studied and developed [11, 16, 19]. Fig. 1 shows the cylinder heads studied in this paper, modeled with three-dimensional continuum elements. The model consists of 35580 elements (Tet10) to improve the accuracy and acceptability of the obtained thermo-mechanical fatigue prediction results. The accurate model selection and usage to define the material behavior (in terms of cyclic and mechanical behavior) is significantly effective in thermal fatigue evaluation.

The description of an elastoplastic cyclic behavior was done using the Chaboche formulation. Such an isotropic/kinematic hardening, which is nonlinear, includes the yield surface motion. This parameter would be relative to the X value in the stress region. Also, as presented in the equation below, the yield surface size alteration would be correlated with the plastic strains [31]:

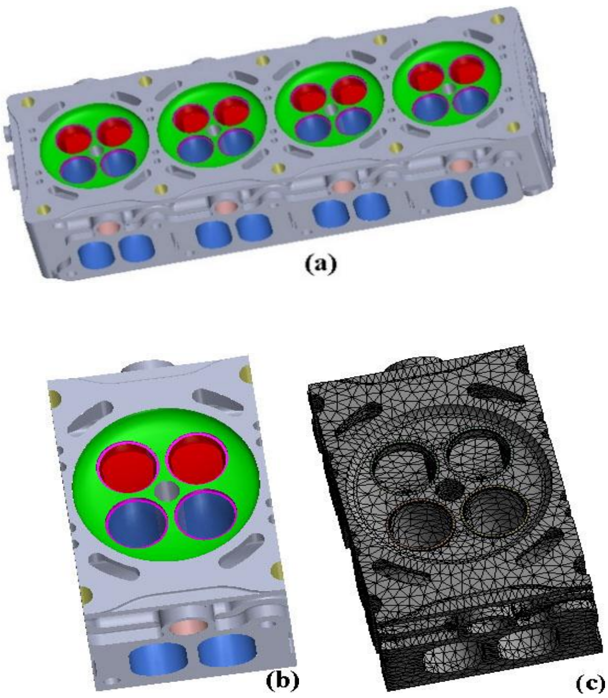

Fig. 1. (a) cylinder head body, (b) the one utilized in finite element analysis, and (c) finite element model

$$\dot{X} = C\frac{1}{\sigma^0}(\sigma_{ij}-\alpha_{ij})\dot{\bar{\varepsilon}}^{PL} - \gamma_{ij}\dot{\bar{\varepsilon}}^{PL} + \frac{1}{C}\dot{C}\alpha_{ij} \tag{1}$$

Where σ^0, $\dot{\bar{\varepsilon}}^{PL}$, C, ã, and $\dot{C}$ represent the yield surface scope, the equivalent plastic strain rate, material constants, and the exchange rate of C in temperature, respectively. Equ. 2 was applied to define the isotropic part, where b and Q represent the material constants [31]:

$$R = \sigma_0 + Q(1-\exp(b\dot{\bar{\varepsilon}}^{PL})) \tag{2}$$

For this model, the f yield criterion is given by the equation [31]:

$$f = |\sigma - X| - k - R \tag{3}$$

Where σ is the stress and k is the primary yield stress.

2- 2- Thermal boundary conditions

The boundary conditions of combustion would be achieved through calculating a full-cycle in-cylinder temperature and the convection heat transfer coefficient. The in-cylinder convection heat transfer coefficient can be computed by the Woschni equation [32]:

$$h_g = 3.26P^{0.8}U^{0.8}b^{-0.2}T_g^{-0.55} \tag{4}$$

Where hg, P, Tg, U, and b are the heat transfer coefficient, the cylinder pressure, temperature, the average speed of the piston, and the bore, respectively. A cycle simulation was used to calculate the cylinder's average gas temperature, enabling the prediction of the instantaneous gas temperature. The integration was then done according to [32]:

$$\overline{T_g} = \frac{1}{4\pi h_g}\int_0^{4\pi} T_g h_g d\theta \tag{5}$$

$$\overline{h_g} = \frac{1}{4\pi}\int_0^{4\pi} h_g d\theta \tag{6}$$

Using the engine function's single-dimensional analysis in GT-POWER software and then applying it to the combustion chamber surface enabled computing the thermal boundary conditions of the gases inside the combustion chamber. The boundary condition of the regions interfacing with oil was defined as 60°C. Moreover, the convection coefficient was $150W/m^2k$ [33]. The heat transfer coefficients of outlet and inlet gases in the exhaust ports and air ports were calculated using the Hirse equation [34]:

$$h = \frac{K}{D(0.158\,\mathrm{Re}^{0.8})} \tag{7}$$

Where K, D, and Re are the thermal conductivity factor, the port's mid-diameter, and the Reynolds number, respectively.

2- 3- Model for TMF life prediction

According to reports, the fatigue on cylinder heads is divided into three failure mechanisms: oxidation damage, creeping damage, and mechanical (plasticity) damage [2, 7]. Based on Sehitoglu's theory, the total damage of components that withstand thermo-mechanical stress (D^{total}) of components that withstand thermo-mechanical stress would be achieved as the sum of mechanical (D^{mech}), oxidation (D^{ox}), and creep damages (D^{creep}) [8, 9]:

$$D^{total} = D^{mech} + D^{ox} + D^{creep} \tag{8}$$

Based on the Basquin-Coffin-Manson relationship, the $\Delta\varepsilon$ mechanical strain range of cyclic deformation is [35]:

$$\Delta\varepsilon = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{\sigma_f'}{E}\left(2N_f\right)^{b} + \varepsilon_f'\left(2N_f\right)^{c} \tag{9}$$

Where $\Delta\varepsilon$ is the strain amplitude σ_f' is the fatigue strength coefficient, E is the modulus of elasticity, $2N_f$ is the number of reversals to failure, b is the fatigue strength exponent, ε_f' is the fatigue strength coefficient and c is the fatigue ductility exponent. Damage resulting from the oxidation would be obtained through the following equation [9]:

$$D^{ox} = \left[\frac{h_{cr}\delta_0}{B\phi^{ox}K_p^{eff}}\right]^{\frac{-1}{\beta}} \frac{2(\Delta\varepsilon_{mech})^{(\frac{2}{\beta})+1}}{\dot{\varepsilon}_{mech}^{1-(\frac{\alpha}{\beta})}} \tag{10}$$

Where h_{cr}, δ_0 ά and B are material parameters, $\dot{\varepsilon}_{mech}$ is mechanical strain rate, and K_p^{eff} is the effective oxidation constant [9]:

$$K_p^{eff} = \frac{1}{t_c}\int_0^{t_c} D_0 \exp\left(\frac{-Q}{RT(t)}\right)dt \tag{11}$$

Where D_0 is a material parameter, Q is the activation energy for oxidation, and R is the universal gas constant. The oxidation phasing factor can be expressed using the following equation [9]:

Table 1. Material constants used in oxidation and creep damages [36]

Parameter	Value
α	0.75(-)
β	1.5(-)
B	0.002s
δ_0	$0.1\mu m s^{-0.75}$
D_0	$60\mu m^2/s$
ξ^{ox}	0.5
ΔH	434Kj/mol
h_{cr}	400 μm

$$\Phi^{ox} = \frac{1}{t_c}\int_0^{t_c} D_0 \exp\left[\frac{-1}{2}\left(\frac{\left(\frac{\dot{\varepsilon}_{th}}{\dot{\varepsilon}_{mech}}\right)+1}{\xi^{ox}}\right)^2\right]dt \tag{12}$$

Where ξ^{ox} and $\dot{\varepsilon}_{th}$ represent the proportion of damage due to differing phases and the rate of thermal strain, respectively. The damage caused by creep is driven through mechanisms, including the expansion of the void and cracking towards the grain boundaries. Expressed as equation (13) [9]:

$$D^{creep} = \Phi^{creep}\int Ae^{(-\frac{\Delta H}{RT})}\left(\frac{\alpha_1\bar{\sigma} + \alpha_2\sigma_H}{K}\right)^m dt \tag{13}$$

Where Ae and m represent material constants, ΔH, $\bar{\sigma}$, σ_H, and K are creep required energy, Mises-based equivalent stress, and hydrostatic and drag stresses, respectively. Moreover, α_1 and α_2 (as the scaling factors) represent the relative damage due to the tensile and compressive stresses, respectively. The creep phase factor is also represented by Φ^{creep} [9]:

$$\Phi^{creep} = \frac{1}{t_c}\int_0^{t_c} \exp\left[\frac{-1}{2}\left(\frac{\left(\frac{\dot{\varepsilon}_{th}}{\dot{\varepsilon}_{mech}}\right)+1}{\xi^{Creep}}\right)^2\right]dt \tag{14}$$

Where ξ^{Creep} shows the phasing shift to creep damage. Table 1 contains the oxidation and creep parameters for Sehitoglu life prediction. The procedure is entirely comprised of thermal and mechanical analyses and fatigue damage, analyzing the TMF life prediction (Fig. 2).

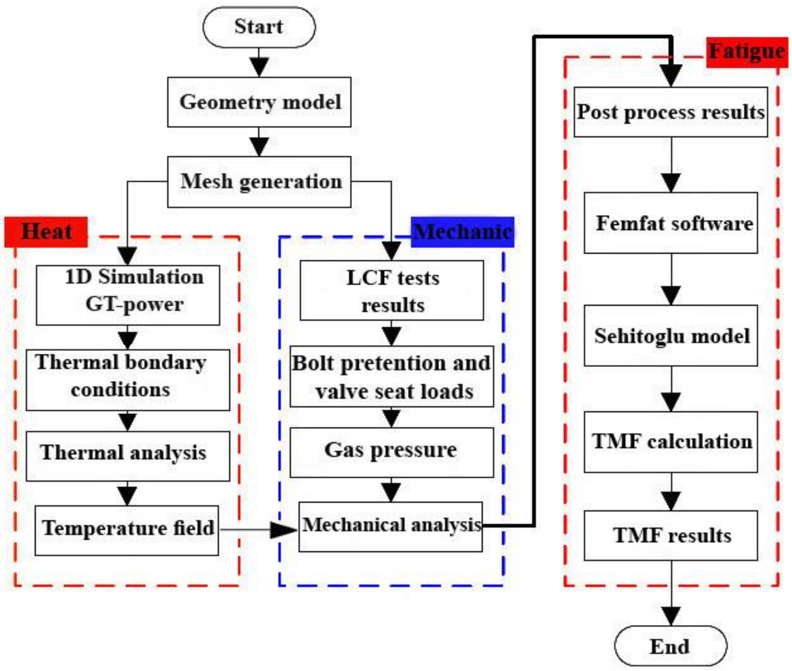

Fig. 2. Flowchart of the TMF analysis procedure

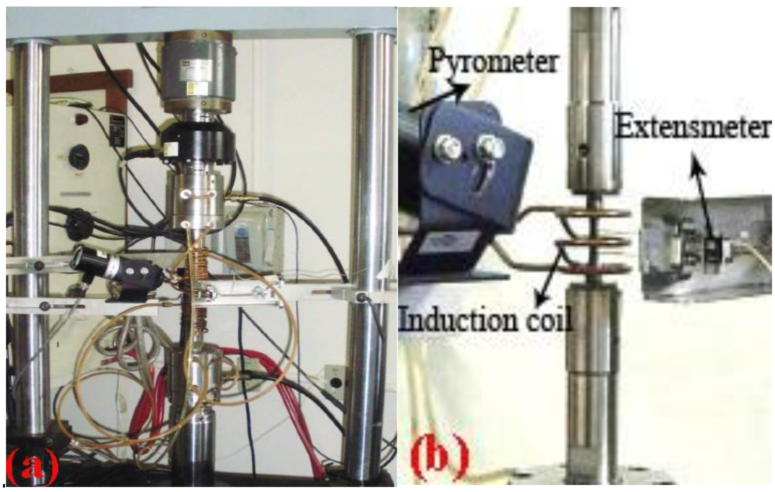

Fig. 3. (a) LCF test equipment and (b) induction coil and extensometer

2- 4- Experimental LCF tests

The present study investigates the application of engine cylinder heads of cast aluminium-silicon-magnesium alloy kind. In the present research, the LCF tests were performed at 25, 200, and 250°C on the aluminum samples. These tests were done under monitoring mechanical strain conditions, according to ASTM E606 standard. As seen in Fig. 3, which illustrates the LCF test equipment, the sample was heated by an induction system. The extensometer at high temperatures was utilized to calculate the mechanical strain.

3- Results and discussion

3- 1- Experimental LCF tests results

The cylinder head material's cyclic behaviors at three temperatures are demonstrated in Fig. 4. Furthermore, Tables 2 and 3 provide details on the Chaboche parameters based on LCF.

3- 2- Thermal analysis

As stated, various thermal and mechanical loadings are applied to the cylinder head, illustrating the extended fatigue life as a significant objective in the cylinder head design.

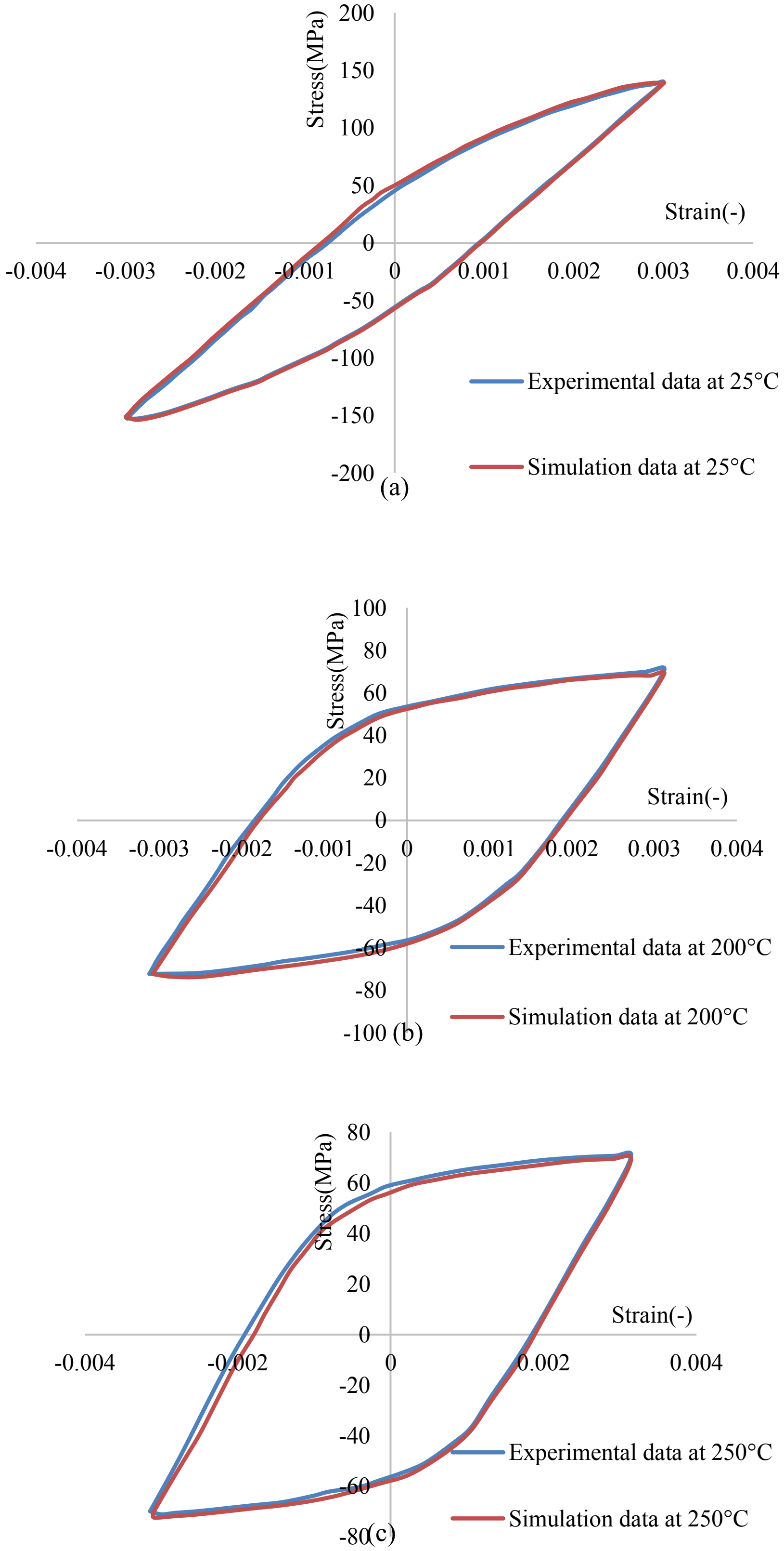

Fig. 4. Experimental and predicted hysteresis at (a) 25°C, (b) 200°C and (c) 250°C

Table 2. Isotropic hardening constants.

Temperature(°C)	20	200	250
E(GPa)	69.2	59.8	53.2
k(GPa)	81.5	48.4	60.6
Q(GPa)	19	1.6	1.1
b(MPa)	16	4.7	-16.5

Table 3. Kinematic hardening parameters

Temperature(°C)	20	200	250
C_1(MPa)	12432	24987	5750
C_2(MPa)	24932	15989	8860
C_3(MPa)	46670	7050	35231
γ_1 (-)	1310	2696	410
γ_2 (-)	1330	21820	3701
γ_3 (-)	1259	313	3890

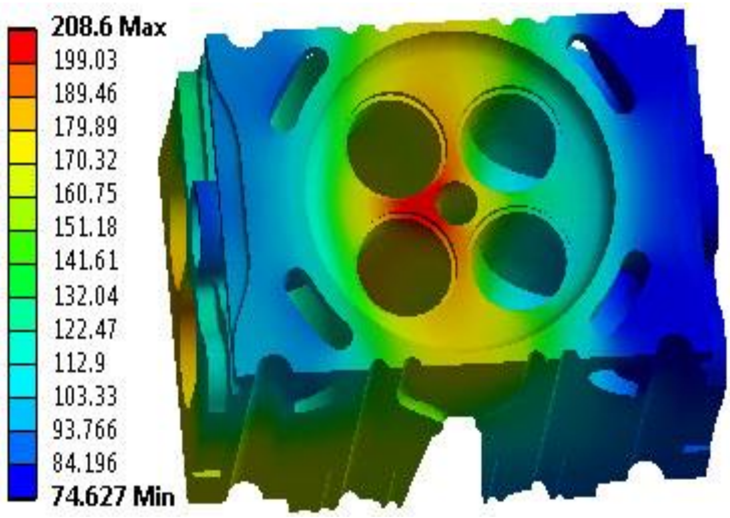

Fig. 5. (a) The temperature distribution in the cylinder head.

Thermal loading significantly impacts the estimating of the cylinder head lifetime. Such an impact from such a highly critical loading would cause thermal stresses and LCF life [5, 6, 19, 37, 38]. Fig. 5 demonstrates the cylinder head's subsequential temperature field. As the figure shows, the highest temperature can be observed between two exhaust valves since the outlet combustion gases are convergent in this area. The highest temperature occurs in the bridge between the exhaust valves, consistent with [1, 5, 7, 12, 18, 19, 21, 37] results. The maximum temperature in the valve bridge between the two exhaust valves reaches 208.6°C, which is within the acceptance limit for aluminum material. Notably, there is a less than 250°C temperature range for operational temperature for aluminum cylinder heads [36]. Thermal loading considerably affects the fatigue life, and the temperature field is identified as a critical region. Crack initiation is caused by the temperature field changes [5-7, 10]. Fig. 6 exhibits this region temperature as a time function of one cycle, representing a full cycle of the engine operation. The decreased temperature in the cylinder head's various sections would lower the thermal stress, which subsequently increases the cylinder head's fatigue life, mostly due to thermal fatigue [5-7, 10].

3- 3- Mechanical analysis

The temperature distribution in the mechanical analysis would be achieved by the thermal analysis considering the mechanical loads that the component endures during the operation. In the finite element model, these loads would be enforced as mechanical ones. The three-phase mechanical analysis initially included the press-fitting of valve seats. The bolt forces would be then applied. The next phase was the increment of the cylinder head's temperature, reaching the maximum temperature. The third phase was applying the combustion pressure to the cylinder head. Its temperature yielded to the ambient at the end [5, 7, 16, 19].

Fig. 7 and Fig. 8 show the Mises and plastic stress and

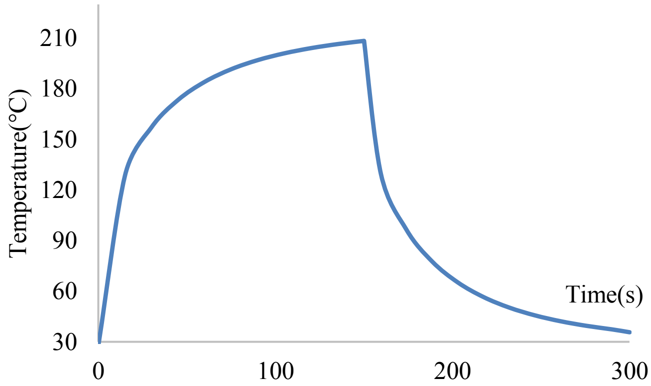

Fig. 6. The temperature at critical node.

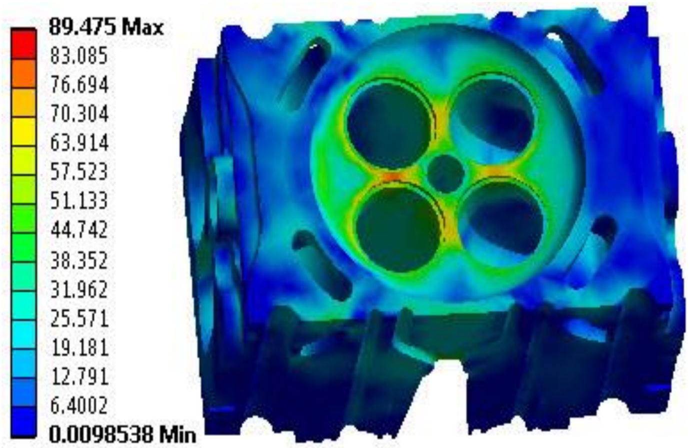

Fig. 7. The Von-Mises stress distribution in the cylinder head.

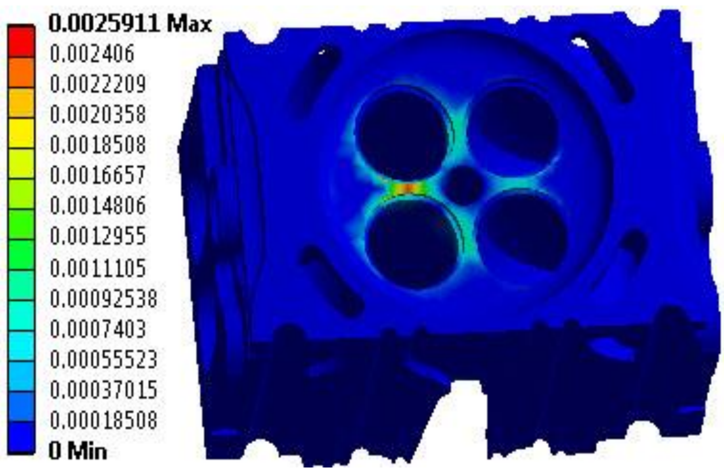

Fig. 8. The plastic strain distribution in the cylinder head

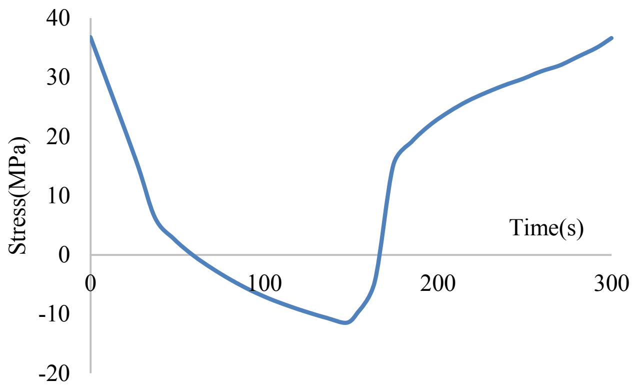

Fig. 9. The normal stress at critical node.

strain distributions, respectively. As seen in Fig. 7, the Mises stress's peak occurs between the valves and the valve seats. The Mises stress reaches its maximum (89.475MPa) in the bridge between exhaust valves. Furthermore, the highest value of the plasticity strain is observed in between the exhaust valves. These zones are located in highly heated regions, suggesting that these points are critical points of the analysis. Accordingly, these areas can be the possible starting points of the fatigue cracks.

The higher than zero equivalent plastic strain shows the material yielding. According to the mechanical analysis, both the stress and plastic strain, which have the dominant effect on the damage evolution, have the highest values in the valve bridge between the two exhaust valves, consistent with [2, 7, 21]. The normal stress (σxx) in the critical region is depicted in Fig. 9, in which the highest temperature can be observed in the 150th second of the operation. Meanwhile, the stress would be compressive due to the thermo-mechanical loading. The assembly loads then cause the stress to be tensile by a gradual decline in the engine temperature (to room temperature) due to its shutting down.

Fig. 10 shows the thermo-mechanical analysis results of selecting the number of elements of the cylinder head. As observed in Fig. 10, as the number of elements increases, the temperature changes are negligible. The stress value does not change significantly by increasing the number of elements more than 35580 elements. Therefore, the best number of elements is 35580.

3- 4- Evaluation of fatigue, oxidation, and creep damages

According to reports, fatigue, oxidation, and creep damage cause the cylinder head's failure [2, 7]. The Sehitoglu model constants and thermo-mechanical analysis results were entered into the FEMFAT software to assess the mechanical, oxidation, and creep damages. Fig. 11 demonstrates the damage distribution of the Sehitoglu model, in which the maximum mechanical, oxidation, and creep damages are $6.45*10^{-6}$, $2.27*10^{-6}$, and $3.44*10^{-7}$, respectively. As a result, the mechanical damage dominantly impacts the thermo-mechanical fatigue life in the studied cylinder head. According to Fig. 11, the highest mechanical damages occur in the bridge between exhaust valves, caused by high plastic strain in this area that makes the area susceptible to fatigue crack. The engine cylinder head is under out-of-phase fatigue. The creep damage can be neglected in out-of-phase fatigue [27] since the fatigue analysis results suggest that the creep damage is negligible compared to mechanical and creep damage. The magnitude of oxidation damage is lower than mechanical, and its maximum is observed betwixt the exhaust valves where the mechanical damage is the maximum. The thermo-mechanical and fatigue analysis results suggest that the area between exhaust valves is the critical area.

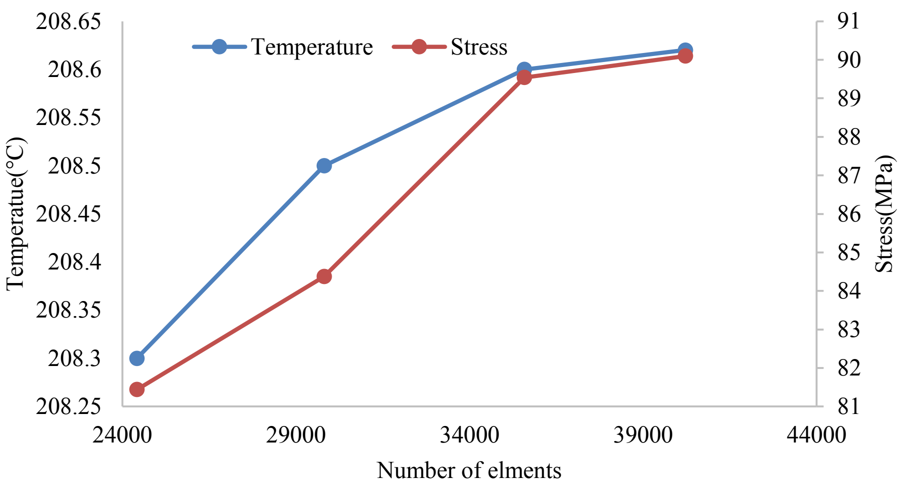

Fig. 10. The Temperature and Von-Mises stress versus number of elements

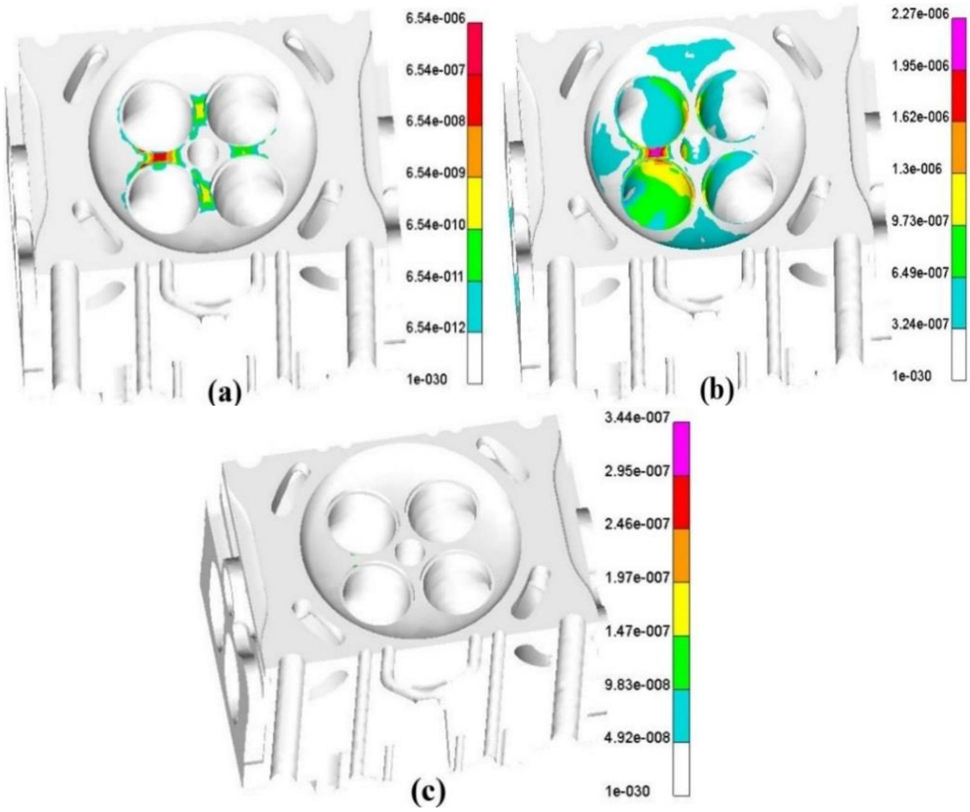

Fig. 11. TMF damage of the cylinder head, (a) mechanical damage, (b) oxidation damage, and (c) creep damage.

Table 4. The percentage of each damage

Temperature(°C)	Values(-)	Percentage(-)
Total damage	9.064×10^{-6}	100
Mechanical damage	6.45×10^{-6}	71.16
Oxidation damage	2.27×10^{-6}	25.04
Creep damage	3.44×10^{-7}	3.79

The percentage of different damages of the Sehitoglu model in this area are given in Table 4, in which mechanical, oxidation, and creep damages have 71.16%, 25.04%, and 3.79% contribution to the total damage, respectively. Fig. 12 shows the statistical histogram of mechanical, oxidation, and creep damages. As stated in Table 4 and Fig. 12, mechanical damage significantly affects the thermo-mechanical fatigue life of the cylinder head. The percentage of oxidation damage is considerable and cannot be excluded. However, the creep damage has an insignificant percentage that can be neglected.

3- 5- Validation

The thermo-mechanical simulation results are compared in Table 5 with results found in reference [38]. As observed from Table 4, there is a good compromise between (finite element analysis) FEA results and data observed on the reference [38].

Based on the mechanical analysis, the area betwixt exhaust valves witnesses the most heightened stress and the plastic strain. The maximum temperature in this area defines the region as a critical one and, hence, prone to fatigue cracks. As seen in the thermo-mechanical and TMF analysis

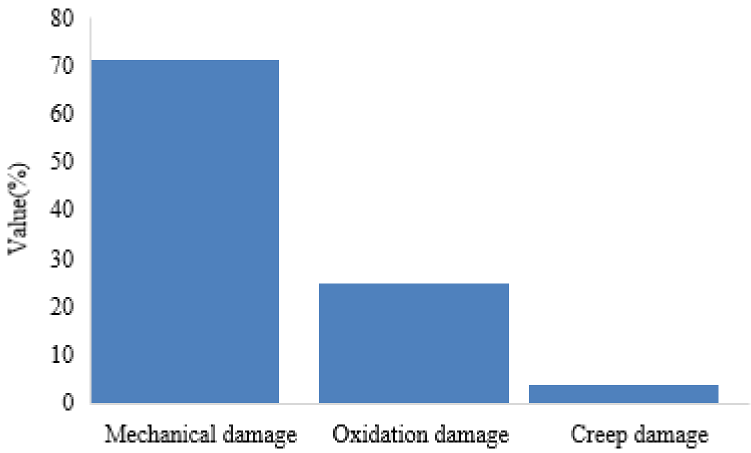

Fig. 12. Statistical histogram of each damage type.

Table 5. Comparison of the finite element analysis results and reference [38]

Temperature(°C)	Values(-)
Maximum temperature	208.6°C
Maximum temperature, reference [38]	206.28°C
Maximum stress	89.475MPa
Maximum stress, reference [38]	92.25MPa

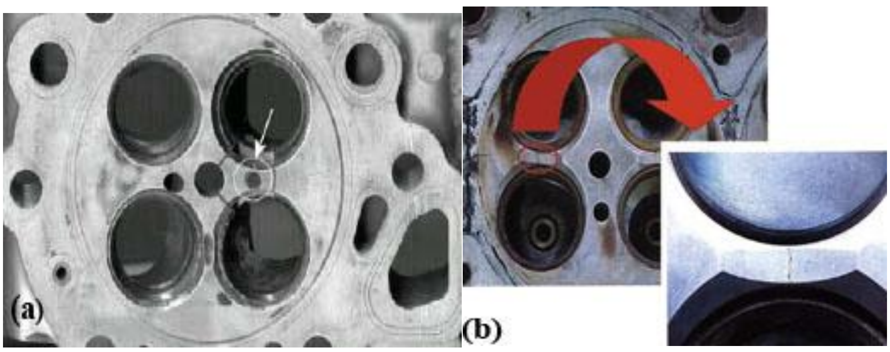

Fig. 13. The cracked cylinder head, a[39], b[40]

(Fig. 7, Fig. 8, and Fig. 11), experimental and empirical tests correspond to the FEA. The cylinder heads that were damaged in the empirical tests are shown in Fig. 13, where the cracks can be seen in the bridge area betwixt the exhaust valves. The cracks' location in the cylinder heads is within the valve bridge.

4- Conclusions

The study investigated TMF life prediction for cylinder heads based on the Sehitoglu model. This model is based on three different damage mechanisms: fatigue, oxidation, and creep, which function together. In this research, the mechanical properties of the cylinder head were obtained by

LCF tests at different temperatures. LCF tests were simulated by ANSYS software, and an excellent agreement was shown between the experimental and simulation results of LCF tests. The FEA demonstrated 208.6°C and 89.475 MPa as the highest temperature and stress in the cylinder head in the valve bridge between exhaust valves. The simulation results demonstrated that the valve bridge between the exhaust valves is susceptible to fatigue cracks. The Obtained finite element analysis results are consistent with the empirical tests, which were performed in the available literature. The FEA showed that the zone with the highest temperature and stress is the area with the lowest TMF life prediction. The [38] outcomes were used to validate the cylinder head's thermo-mechanical analysis results, suggesting that the thermal and mechanical analysis errors were 1.12% and 3.01%, respectively. The minimum total TMF damage is predicted as $9.064*10^{-6}$ at the critical area. The maximum mechanical, oxidation, and creep damage values were determined as $6.45*10^{-6}$, $2.27*10^{-6}$, and $3.44*10^{-7}$, respectively. The thermo-mechanical fatigue life analysis displayed 71.16, 25.04, and 3.79 percentages for the mechanical, oxidation, and creep damages, respectively. The thermo-mechanical fatigue results state that the mechanical damage dominantly impacts the thermo-mechanical fatigue life of the cylinder head. The numerical results suggest that the percentage of oxidation damage is considerable and cannot be excluded. The creep damage percentage, on the other hand, is insignificant and negligible. The minimum cylinder head's mechanical fatigue life in the critical region of exhaust valves was predicted as 155038 cycles using the Sehitoglu model.

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