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Original Research

Thermo-mechanical fatigue life prediction for exhaust manifold based on Sehitoglu model considering oxidation and creeping damages

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ABSTRACT

The exhaust manifolds are subjected to higher thermal stress than before, due to the increasing engine power output, fuel consumption, and gas emission. Thus, simulation and analysis of fatigue cracks are essential. In this paper, thermo-mechanical fatigue (TMF) life analysis of the exhaust manifold is performed by using finite element method (FEM) and ABAQUS software to predict the temperature and stresses and then TMF fatigue life by using Sehitoglu theory and FEMFAT software. Mechanical properties of High silicon molybdenum (HiSiMo) ductile cast irons (DCI) obtained by LCF and tensile tests at different temperatures. The results of finite element analysis (FEA) showed that the maximum temperature and stress values in the exhaust manifold are 757.4 °C and 321.8 MPa and the position is at the confluence region. The numerical results showed that the area where the maximum temperature and stress occur is where the least TMF life is estimated. The obtained TMF results proved that mechanical damage plays a leading role in the total TMF life of the exhaust manifold. The oxidation damage was greater than the creep damage which is not negligible.

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1- Introduction

The exhaust manifolds are one of the most serious automotive parts, which collect waste gases from the engine cylinders and send them to the exhaust system. They play an important role in the performance of the automotive engine. Especially, gas emission system output and engine fuel consumption depend on exhaust manifold design [1, 2]. The exhaust manifolds are subjected to thermo-mechanical loads. Cyclic fluctuations in thermal loads, which are the result of turning the automotive on and off, create thermo-mechanical fatigue loads on the engine exhaust manifolds, making them appear to have the subject of exhaust manifold fatigue cracks or fractures [3-6]. Nowadays exhaust manifold failure increases due to the higher exhaust gas temperature. Therefore, TMF is a very important problem. If a part is not properly designed, fatigue cracking could happen at a very early stage [5, 6].

High silicon molybdenum ductile cast irons are widely used for high-temperature engine parts, such as exhaust manifolds which withstand cyclic TMF loads during engine operation. It is essential to investigate the TMF behavior of HiSiMo DCI to accurately predict the thermo-mechanical fatigue life and durability of high-temperature engine parts [7, 8].

In the references, previous investigations report several studies related to thermal stress and TMF in engine exhaust manifolds. Chen et al. established the simulation approach for the fatigue life assessment of cylinder heads with integrated exhaust manifolds. Their research proved an acceptable between experimental and simulation results [9].

The impact of perimeter fins on LCF life for exhaust manifolds was studied by Ashouri. His simulation proved that the number of failure cycles for the modified exhaust manifold is approximately 55% higher than the results obtained for the original exhaust manifolds [10].

Luo et al. evaluated failure analysis and optimization of exhaust manifold based on CFD and FEM analysis. It can be concluded that the failure of the exhaust manifold was mainly due to thermal-mechanical fatigue [6]. Multiple 3D-DIC systems for measuring the displacements and strains of an engine exhaust manifold are designed by Zhang et al. It showed that 3D-DIC is reliable and can provide whole-field contour data [1]. The thermal map of an exhaust manifold was studied by Banuelos et al. A good correlation was shown between the experimental and simulated results [2]. Öberg et al. Examined creep effect for the exhaust manifold. There was no difference between monotonic and cyclic creep rates [11].

Evaluation of TBC in LCF life for exhaust manifold was done by Ashouri. The obtained LCF results proved that the number of failure cycles for coated exhaust manifolds is almost in order twofold, compared to the exhaust manifolds that were not coated [12].

Thermo-mechanical fatigue Testing of Welded Tubes for Exhaust Applications was performed by Quan et al. There was a good agreement between the experimental observations and simulated results [13].

Liu et al. performed a thermo-mechanical fatigue analysis on a ductile cast iron exhaust manifold. TMF damage analysis indicated that the predicted TMF life is close to EMD dynamometer tests within a factor of 2 [5].

Assessment of thermal fatigue fracture for exhaust manifolds was performed by Castro Güiza et al. Their simulation proved that some areas of the exhaust manifold entered into the yield region [4]. Ashouri investigated the impact of temperature on modal analysis for the exhaust manifold. The results of FEA demonstrated that gas pressure must be considered in exhaust manifold analysis [14].

Salehnejad et al. Developed a finite element theory to analyze the failure of an exhaust manifold. Their study ruled out the possibility of failure in all spots [15].

TMF simulation of manifolds was investigated by Ashouri. The results of FEA revealed that temperature and thermal stresses have critical values in the confluence area [16].

Kurihara et al. developed a method to predict the fatigue strength of motorcycle exhaust manifolds considering vibration and thermal stress. According to their research, the experimental and simulated results match [3]. Thermo-mechanical analysis of exhaust manifold using two different elasto-viscoplastic theories was studied by Mao et al. It is proved that the Chaboche and Sehitoglu theories give very similar results [17].

Thermo-mechanical high cycle fatigue analysis of the exhaust manifold of a turbocharged engine with two-way coupling FSI was studied by Naderi Hagh et al. It is proved that the temperature and thermal stresses have the most critical values at the confluence region [18].

Joshi et al. studied failure analysis and robust optimization of an exhaust manifold diffuser plate. Metallurgical failure analysis coupled with thermal fatigue analysis of the component concluded that thermal fatigue is the root cause of the failure [19].

Optimization of exhaust system hangers for reduction of vehicle cabin vibrations analyzed by Shojaeifard et al. Simulated results indicated that optimization of the locations has resulted in a significant decrease in hanger loads, significantly reducing the vibrations transmitted to the vehicle cabin and increasing the life of the rubber hangers [20].

Partoaa et al. investigated the effect of fin attachment on the thermal stress reduction of exhaust manifolds. Their research proved that the combined modifications, i.e. the thickness increase and the fins attachments, decrease the thermal stresses by up to 28% and the contribution of the fin attachment in this reduction was much higher compared to the shell thickness increase [21].

Padmanabha et al. studied the effect of mullite coating on the thermal stress on the exhaust manifold. Around 20% depletion in thermal stresses is shown in the coated circular exhaust manifold around the uncoated circular exhaust manifold [22].

Comparing the temperature distribution of the coated exhaust manifold proved that the coating with a thickness of 250 μm has better results than other TBCs [23]. The thermal map of an exhaust manifold was studied by Banuelos et al. A good correlation was shown between the experimental and simulated results [2].

Thermo-mechanical analysis of the exhaust manifold and catalyst with fluid-structure interaction was performed by Mohammadi and Salehnejad. A good correlation was proved between the experimental and simulated thermal analysis results [24].

According to reports, the fatigue on the exhaust manifold is divided into three different failure mechanisms: oxidation damage, creeping damage, and mechanical (plasticity) damage [1, 5, 8, 18, 19]. In the past, some studies have focused on plasticity, whereas oxidation and creep have been significantly less studied. Thus, this article aims to simulate the TMF behavior of HiSiMo DCI based on the Sehitoglu theory. As stated by Sehitoglu, a deeper study of the different mechanisms affecting the behavior of materials under TMF loading conditions is essential [25, 26]. In this article, thermo-mechanical fatigue analysis of the exhaust manifold is performed by using finite element method (FEM) and ABAQUS software to predict the temperature and stresses and then TMF fatigue life by using Sehitoglu theory and FEMFAT software.

2- Methodology

2-1- The material behavioral model

A nonlinear isotropic-kinematic hardening material model is applied in this paper. When the material is yielding the equation of yield surface (f), is given by [27]:

$$f = \sqrt{\frac{3}{2}\left(S\text{-}X'\right)\left(S\text{-}X'\right)} - R - k = 0 \tag{1}$$

where S and X' are deviatoric parts of stress and back stress tensors respectively, R is isotropic hardening variable, and k is the initial size of the yield surface. The evolution of back stress tensor is defined by the expression [27]:

$$\dot{X}_i = \frac{2}{3} C_i \dot{\varepsilon}_p - \gamma_i x_i \dot{p} + \frac{1}{C_i(T)} \frac{\partial C_i}{\partial T} X \dot{T} \tag{2}$$

where C and γ are material properties. The term $\gamma_i \dot{p}$, called the dynamic recovery, causes the nonlinear response of the stress–strain behavior. Overall back stress tensor is a linear combination of individual back stress tensors, as below [27]:

$$X = \sum_{i=1}^{m} X_i \tag{3}$$

where i is the number of back stress tensors. The evolution of the isotropic hardening variable (R), with material constants Q and b, is given by relation [27]:

$$\dot{R} = b(Q - R)\dot{p} \tag{4}$$

Heat transfer in exhaust manifolds is defined by three factors: conduction through the manifold metal, convection from the hot exhaust gases, and radiative exchange between different parts of the exhaust manifolds [28, 29]. Heat transfer by conduction per unit area per unit time, in the steady situation is described by the Fourier equation [29]:

$$\dot{q} = -k \nabla T \tag{5}$$

where k is the thermal conductivity and ∇T is the temperature difference. The standard Stefan–Boltzmann law expresses heat loss due to thermal radiation between the inner wall of the manifold and the ambient [29]:

$$\dot{q} = \varepsilon \sigma \left(T_g^4 - T_a^4 \right) \tag{6}$$

where ε is the emissivity, σ is the standard Stefan–Boltzmann constant, T_g is the manifold temperature and T_a is the air temperature. Heat convection from exhaust gas to manifold wall can be defined with the following equation [30]:

$$k \frac{\partial T}{\partial n} = h\left(T_g - T_a \right) \tag{7}$$

2-2- Model for TMF life prediction

TMF is the case of fatigue failure due to cyclic changes in thermo-mechanical loading. The life prediction of TMF loading cases has received considerable attention in recent years mainly in engine parts [5, 6]. Many studies showed that high temperature fatigue damage consists of three mechanisms: fatigue damage, oxidation damage and creep damage [1, 5, 8, 18, 19]. Based on Sehitoglu theory, the total damage (D^{total}) of components withstand thermo-mechanical stress is computed as the sum of mechanical damage(D^{mech}), damage caused by oxidation(D^{ox}) and damage due to creep processes(D^{creep}) [25, 26]:

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

Based on the Basquin-Coffin-Manson relationship, the mechanical strain range $\Delta\varepsilon$ of cyclic deformation is [31]:

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

where σ'_f is the fatigue strength coefficient, b is the fatigue strength exponenperfatigue strength coefficient and c is the fatigue ductility exponent. Damage caused by oxidation is calculated in accordance with the Eq. 10 [26]:

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

where h_{cr}, δ_0, α and B are material parameters, $\dot{\varepsilon}_{mech}$ is mechanical strain rate, and $K_p^{eff}$is the effective oxidation constant [26]:

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

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 Eq. 12:

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

where ξ^{ox} is a measure of the proportion of damage due to differing phases and $\dot{\varepsilon}_{th}$ is the rate of thermal strain. Creep damage is caused by mechanisms such as void growth and cracking along grain boundaries and this relation given as Eq. 13 [26]:

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

where A_e and m are material constants, ΔH is activation energy for creep, $\bar{\sigma}$ is equivalent stress according to Mises, σ_H is hydrostatic stress, and K is drag stress. α_1 and α_2 are scaling factors that represent the relative proportion of damage caused by tensile and compressive stress. Φ^{creep} is the creep phase factor [26]:

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

where ξ^{creep} defines the sensitivity of the phasing shift to creep damage. The oxidation and creep parameters for Sehitoglu life prediction are tabulated in Table1.

Table 1 Material constants used in oxidation and creep damages [32]

Parameter	Value	Parameter	Values
α	0.27(-)	ξ^{ox}	0.33
β	1.3(-)	ΔH	434 kj/mol
B	$4.93\times10^{-3}s^{-0.5}$	A_e	$8.8\times10^{28}\,s^{-1}$
δ_0	$1.24\times10^{-6}\,\mu m.s^{-0.75}$	α_1	9.04
D_0	$2.94\times10^{7}\,\mu m^2/s$	α_2	856

2-3- Experimental LCF and tensile tests

In this paper, the tensile tests were done for evaluating the mechanical properties of the exhaust manifold material according to ASTM E8-E8M standard at 30, 400 and 600 °C. The same specimen geometry in accordance with the ASTM E 606 standard was used for determining the LCF parameters. Tensile and LCF tests were conducted using a servo-hydraulic MTS 810 material machine (Fig. 1). In The LCF tests, the strain rate was 3×10^{-3} 1/s. During tests, the temperature was measured by an infrared pyrometer and a high temperature extensometer was used for measuring the strain. An induction system was applied for heating the specimen.

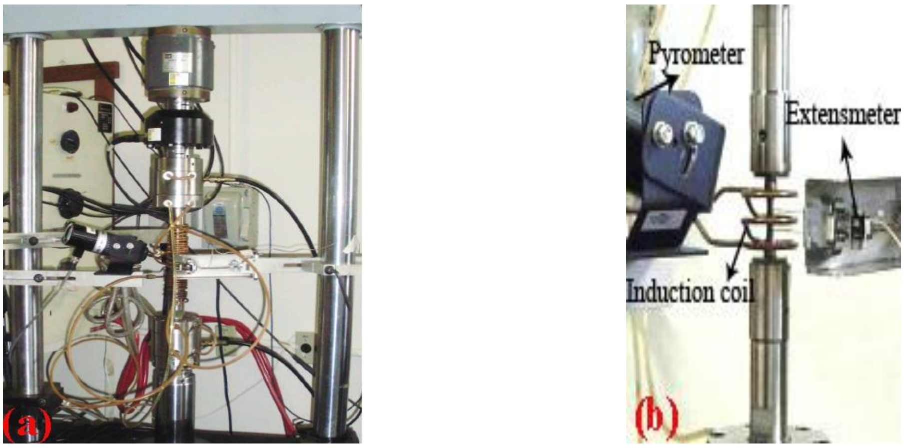

Figure 1 (a) Material testing machine MTS 810 and (b) induction heater and extensometer

3- Results and Discussion

3-1- Experimental LCF and tensile tests results

Figure 3 depicts the HiSiMo DCI stress-strain curves at three temperatures (30, 400 and 600 °C). The Cyclic bahaviors of the HiSiMo DCI at three temperatures are shown in Fig. 4.

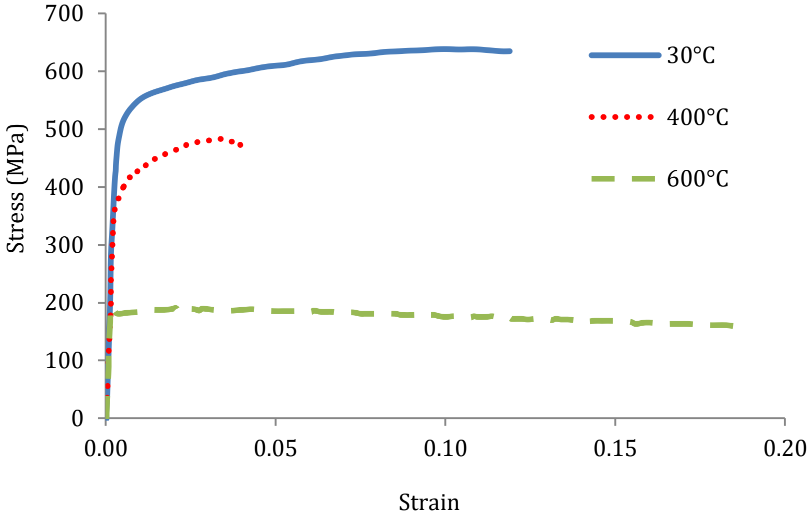

Figure 3 Stress-strain curves in tensile test of HiSiMo DCI at 30, 400 and 600°C

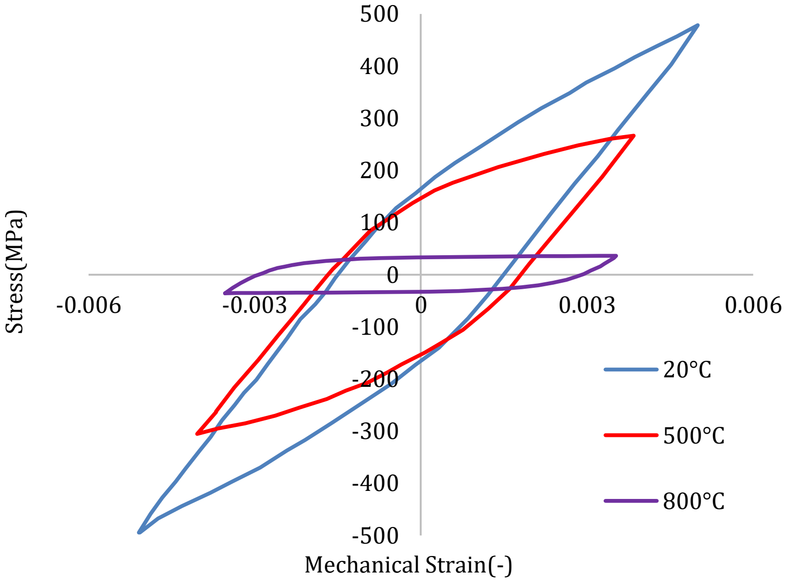

Figure 4 Cyclic bahaviors o the HiSiMo DCI at 30, 500 and 800 °C

The tensile properties of the HiSiMo DCI at different temperatures are summarized in Table 2. In Table 3, isotropic hardening parameters of the HiSiMo DCI based on LCF tests are reported.

Table 2 Tensile properties of the HiSiMo DCI

Temperature (°C)	30	400	600
E (Gpa)	168	154	139
0.2% Proof strength (MPa)	412	326	175
Elongation (%)	14	13	31

Table 3 Isotropic hardening parameters of the HiSiMo DCI

Temperature (°C)	20	500	800
E (Gpa)	142.7	137.28	139
k (MPa)	256.7	326	175
b (-)	0.3	15.8	0.5
Q (Mpa)	42.6	-20.7	-31.1

There are several methods to insert the values of C and γ into Abaqus software that one of them is entering yield stress at plastic strain using LCF test results [16]. The yield stress at plastic strain was extracted from LCF test results and entered into the Abaqus software.

3-2- Apply bolt pretension

In the first step of the analysis, each of the seven bolts is fastened to a uniform bolt force of 20 kN. The clamping forces introduced by bolts fastening and the material expansion–contraction due to temperature variation during the engine operation are the main loads for thermo-mechanical analysis of exhaust manifolds [16]. A typical manifold bolt behavior is shown in Figure 5.

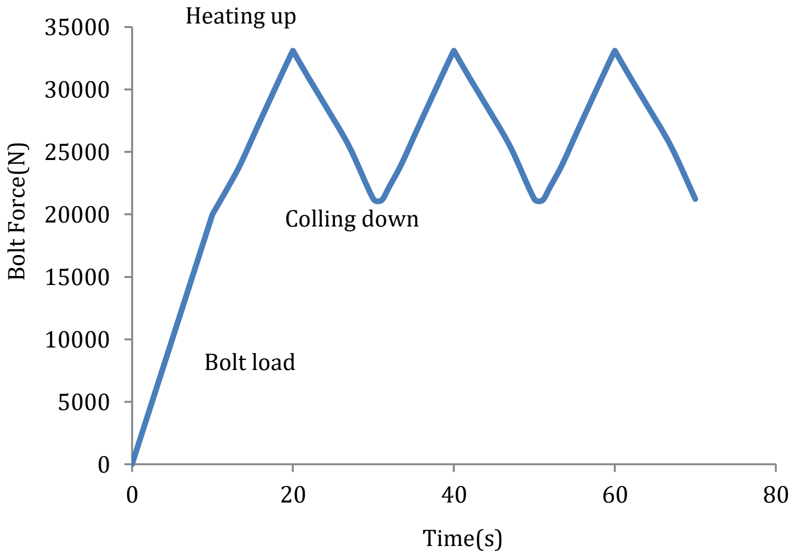

Figure 5 Typical force variation for manifold load

3-3- Thermal Analysis

Thermal stresses in the engines exhaust manifolds are the most important stresses, leading to LCF in the exhaust manifolds. It is also important to evaluate the exhaust manifolds temperature field in order to detection the thermal stresses and fatigue life within allowable limit. Thus, the first step of a TMF analysis is a thermal analysis with the goal to evaluate the temperature field for the exhaust manifold. The temperature field not only shows critical spots but also specifies the limitation of the number of cycles to fatigue failure [2, 4, 5, 6, 12, 16]. The hot exhaust gases apply a heat flux created to the inner wall of exhaust manifolds. This heat flux is considered applying a surface-based film condition, with a constant temperature of 816°C and a film condition of $500*10^{-6}$ W/mm^2°C. The temperature boundary conditions of 355°C and 122°C is used at the flange surfaces attached to the cylinder head and exhaust manifold, respectively [10, 12, 16, 33, 34]. Contour results of the temperature distribution are given in Figure 6. As expected, the temperature maximum is occurred in the confluence region. This corresponds to the results by [6, 10, 12, 14, 16, 33, 34].

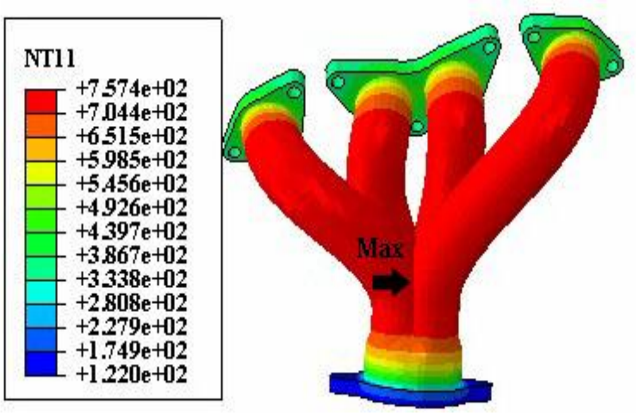

Figure 6 The temperature distribution

3-3- Mechanical analysis

The exhaust manifolds withstand the mechanical stress and tolerate the thermal stress due to the temperature fluctuations. Thus, the evaluation of thermo-mechanical coupling stress on the exhaust manifolds is essential. Stresses and strains created by thermal distribution and mechanical loads are determined by mechanical analysis [4, 5, 6, 12]. It is assumed that the exhaust manifolds are constrained to the cylinder head and catalyst, so the flange surfaces are fixed in the normal direction to the cylinder head and catalyst but are free to move in the two lateral directions [10, 12, 16]. The structural boundary conditions used to finite element model are given in Figure. 7. Figure. 8 shows the Von-Mises stress field at end of second step.

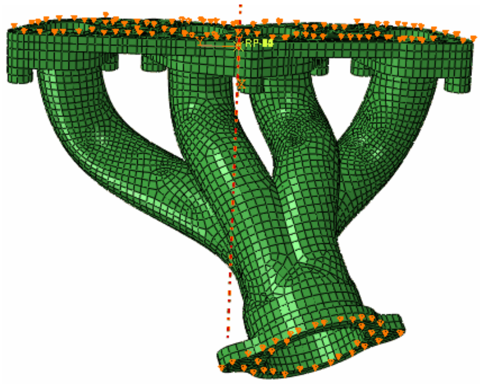

Figure 7 Structural boundary conditions

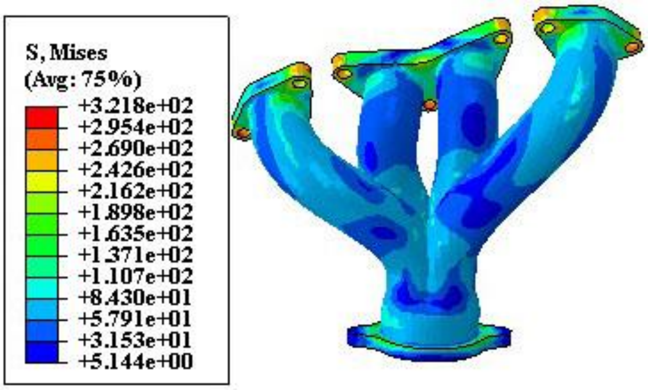

Figure 8 The Von-Mises stress distribution

The maximum value of Von-Mises stress in the exhaust manifolds is calculated 321.8MPa. The maximum Von-Mises stress was at the confluence area of the exhaust manifolds, except for the areas around the screws where there was stress concentration. This corresponds to the results by Ashouri (2018, 2019, 2021). Based on the source [16] the first fatigue cracks can be seen at the hottest spot of exhaust manifolds (Figure 5). This region is also located in the confluence region. The equivalent plastic strain distribution in the exhaust manifold is given in Figure 9, which is simulated after applying the thermal cycle reported by the previously predicted thermal analysis. The equivalent plastic strain is greater than zero, showing that the material is currently yielding [10, 16]. The study of mechanical analysis results, it can be seen that both the stress and plastic strain, which have the important effect on the fatigue life are maximum in the confluence region.

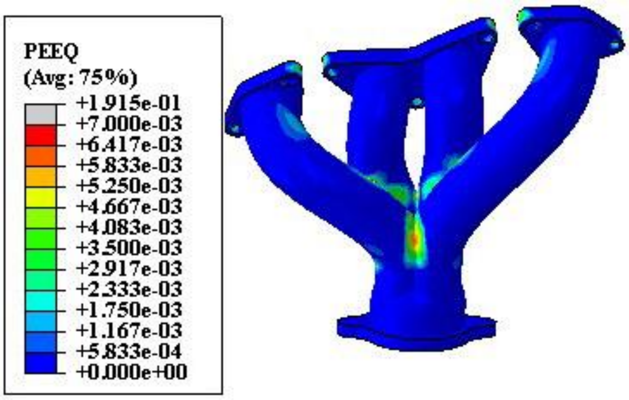

Figure 9 The equivalent plastic strain distribution

3-4- TMF life prediction

Sehitoglu TMF model is according to the three different damage mechanisms (fatigue, oxidation and creep) that are acting together. Depending on the temperature strain rate, strain amplitude and phasing, these damage mechanisms can have various parts in the total damage, which is the sum of these components [18, 19]. The purpose of TMF analysis is to predict fatigue life and identification of design measures for the durability of the exhaust manifold for a given thermal shock test. As it has been seen in experimental test, the exhaust manifold is failed like Figure 10. This is due to the maximum principal strain on the critical element which is demonstrated in Figure 11 obtained from ABAQUS software at high temperature of the manifold.

Figure 10 Hair-line crack in thermal shock test [35]

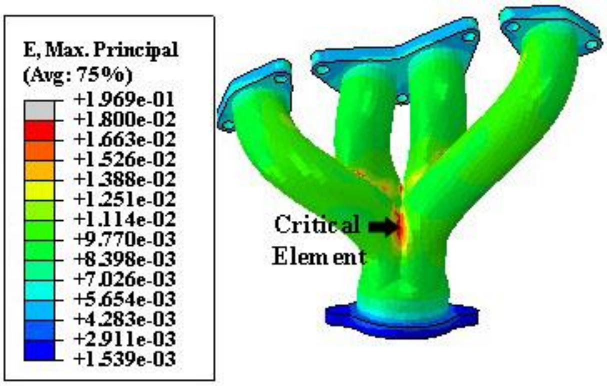

Figure 11 The Maximum principal strain distribution

The TMF life analysis is predicted by using HEAT module in FEMFAT software. As it's shown in Figure 12, the TMF life in the critical element is under 10^4 and 10^5 which shows LCF for the exhaust manifolds [31]. As shown in Figure 13, mechanical damage plays a leading role in total TMF life of the exhaust manifold. According to the Figure, it is clear that the oxidation damage is greater than the creep damage.

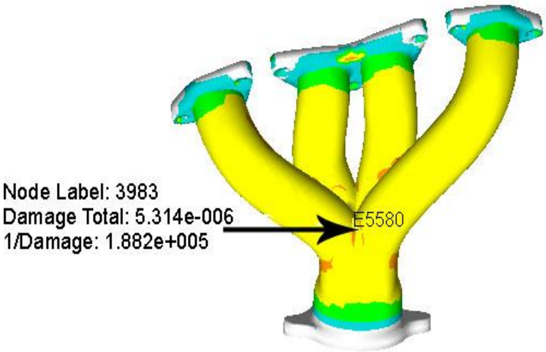

Figure 12 TMF life in the critical element

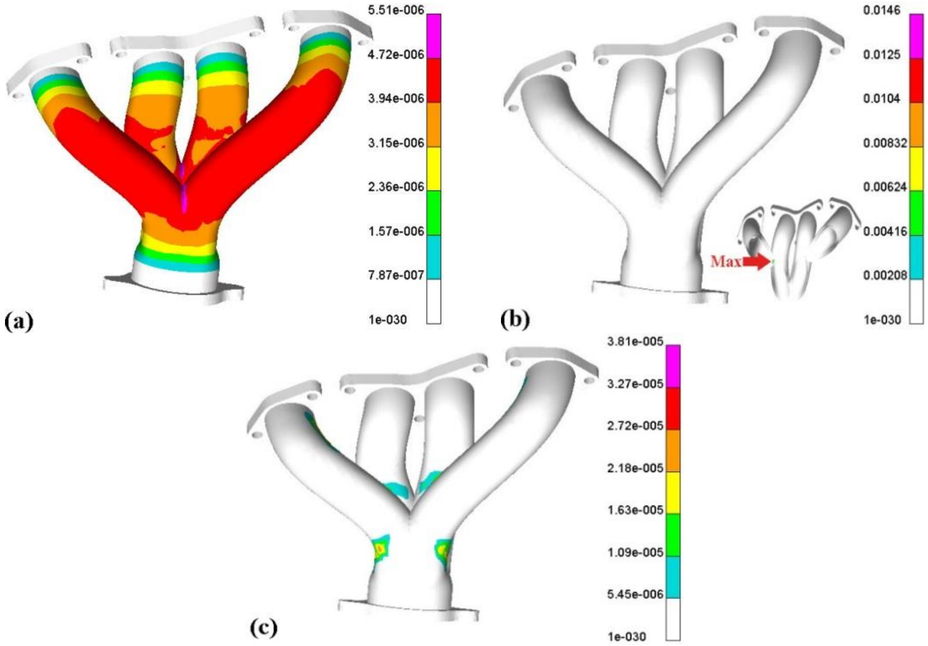

Figure 13 TMF damage of the exhaust manifold, (a) oxidation damage, (b) mechanical damage and (c) creep damage

The materials used in the exhaust manifold must have high temperature strength and oxidation resistance. The primary aim in material selection is not to reach the unusual oxidization area under different engine operating conditions [5, 36, 37]. Oxidation damage are typically eliminated through the use of materials which have a higher environmental resistance. However, since oxidation damage is primarily dependent on temperature of the exhaust manifold, practical solutions with local design modifications are very difficult [36]. The exhaust manifold temperatures can rise rapidly from ambient temperature to around 900°C, so exhaust manifold requires excellent heat resistance, great oxidation resistance, and prominent creep performance [37]. Although there are studies showing creep damage as the dominant factor for the total damage, some other studies indicate that plasticity has major contribution on fatigue failures of exhaust manifold [36, 37].

4- Conclusions

In this paper TMF life prediction for exhaust manifold based on Sehitoglu model is studied. This theory is according to the three different damage mechanisms: fatigue, oxidation and creep that are acting together. In this research, mechanical properties of HiSiMo DCI obtained by LCF and tensile tests at different temperatures. The results of the thermo-mechanical analysis proved that the maximum temperature and stress exist in the confluence area. The FEA results showed that the area where the maximum temperature and stress is occurred is where the least TMF life is predicted. The obtained TMF results proved that the mechanical damage plays an important role in total TMF life of the exhaust manifold. The oxidation damage was greater than the creep damage. Finite element analysis provides accurate and reliable prediction of temperature and fatigue life prediction in the engine exhaust manifold. The TMF life of this part can be predicted through finite element analysis instead of experimental TMF tests.

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مقاله پژوهشی

پیش‌بینی عمر خستگی ترمومکانیکی چندراههٔ دود براساس الگوی سیتقلو با آسیب اکسیدشدن و خزش

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اطلاعات مقاله

کلیدواژه‌ها:
خستگی ترمومکانیکی
تحلیل اجزای محدود
چندراههٔ دود
نظریهٔ سیتقلو

چکیده

امروزه چندراههٔ دود تنش حرارتی بیشتری را نسبت به گذشته تحمل می‌کند. علت این امر افزایش قدرت خروجی موتور، کاهش مصرف سوخت و گازهای آلاینده است. بنابراین شبیه‌سازی و تحلیل ترک‌های خستگی ضروری است. در این پژوهش، تحلیل عمر خستگی ترمومکانیکی چندراههٔ دود با استفاده از روش اجزای محدود و نرم‌افزار آباکوس به منظور پیش‌بینی دما و تنش و سپس عمر خستگی ترمومکانیکی با استفاده از نظریهٔ سیتقلو و نرم‌افزار فمفت انجام شده است. خواص مکانیکی چدن داکتیل (HiSiMo) با استفاده از آزمون‌های خستگی کم‌چرخه و کشش در دماهای مختلف بدست آمده است. نتایج تحلیل اجزای محدود نشان داد که بیشینهٔ دما و تنش در چندراههٔ دود بترتیب ۷۵۷٫۴ درجهٔ سانتیگراد و ۳۲۱٫۸ مگاپاسکال است و موقعیت آن در ناحیهٔ همریختگاه است. نتایج شبیه‌سازی شده نشان داد که حداقل عمر خستگی ترمومکانیکی در ناحیه‌ای که دما و تنش بیشینه است، رخ می‌دهد. نتایج تحلیل خستگی ترمومکانیکی ثابت کرد که آسیب مکانیکی نقش برجسته‌ای در خستگی ترمومکانیکی چندراههٔ دود دارد. آسیب اکسیدشدن از آسیب خزش بیشتر بود و قابل چشم‌پوشی نیست.

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