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Improving High Cycle Fatigue Life in An Exhaust Manifold Using Perimeter Fins with Considering Stress Gradient

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Abstract: The effect of perimeter fins on the thermal stress and High Cycle Fatigue (HCF) life in an exhaust manifold with considering stress gradient was investigated. For this purpose, coupled thermo-mechanical analysis of an exhaust manifold was carried out. Then HCF life of the component was predicted using a standard stress-life analysis and results were compared to the original exhaust manifold. Mechanical properties of exhaust manifold material were obtained by tensile tests at different temperature. The results of the thermo-mechanical analysis proved that the maximum temperature and stress are visible in the confluence region. The obtained Finite Element Analysis (FEA) proved the fact that perimeter fins reduce the temperature distribution in the exhaust manifolds about 31°C. As a result, the exhaust manifolds tolerate lower temperature and fatigue life will increase. The results of FEA indicated that the stress in the modified exhaust manifolds decreased approximately 19MPa for the sake of depletion of temperature gradient, which can lead to higher fatigue lifetime. The results of HCF showed that the number of cycles of failure for modified exhaust manifold is approximately 63% higher than the results obtained from the original exhaust manifolds. The results of the FEA analysis are compared with the real sample of the cracked exhaust manifold to properly evaluate the results, and it has been shown that critical identified areas correspond to the failure areas of the real sample.

Keywords: Exhaust Manifold, High Cycle Fatigue Life, Perimeter Fins, Stress Gradient

Biographical notes: Hojjat Ashouri received his PhD in Mechanical Engineering from University of IAU Science and Research Branch 2016. He is currently Assistant Professor at the Department of Mechanical Engineering, Varamin-Pishva, Iran. He received his MSc in Mechanical Engineering from Urmia University in 2005. He received his BSc in Mechanical Engineering from Tabriz University in 2002. More than 20 journal papers, 9 accepted conference papers, 3 published book and one patent are the results of his researches so far. His current research focuses on finite element analysis, low and cycle fatigue, optimization and engine simulations.

Research paper

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 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 engines exhaust manifolds, making them appear to have the subject of exhaust manifold fatigue cracks or fracture [3-6]. Thermo-mechanical loading is frequently defined to be in-phase (IP) or out of phase (OP). In IP loading, the maximum temperature and strain happen at the same time. In OP loading, the material undergoes tension at lower temperatures and compression at highest temperature [7]. Exhaust manifolds endure OP thermo-mechanical loads [8]. If a part is not properly designed, fatigue cracking could happen at very early stage [5-6]. The fins are extended surfaces that are used to dissipate heat from the primary surface to the surrounding environment. They increase the area of heat transfer and cause an increase in the transferred heat amount. Adding a fin to the object, however, increases the surface area and can sometimes be an economical solution to heat transfer problems [9].

In the references, previous investigations report several studies related to the thermal stress and TMF in engines 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 agreement between experimental and simulation results [10]. The impact of perimeter fins on LCF life for exhaust manifold 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 [11]. 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]. 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 exhaust manifold. There was no difference between monotonic and cyclic creep rates [12]. 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 the order twofold, compared to the exhaust manifold which were not coated [13]. 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 [14].

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 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 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 [15].

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 [16]. TMF simulation of manifolds was investigated by Ashouri. The results of FEA revealed that temperature and thermal stresses have the critical values in the confluence area [17]. Kuribara et al. developed a method to predict fatigue strength of motorcycle exhaust manifold considering vibration and thermal stress. According to their research, the experimental and simulated results match [3]. Thermo-mechanical high cycle fatigue analysis of exhaust manifold of 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 [8].

According to the reviewed literature, different characteristics of exhaust manifolds such as geometry, materials and areas of inlet and outlet ports affect the manifold fatigue life. Modifications like increasing the thickness of the manifold solid wall and improvement of heat transfer significantly decrease the manifold thermal stresses. The increased thickness solely could not harness the thermal stresses as there is a limitation for increasing the wall thickness [11]. Thus, This paper aims to investigate the effect of fin attachment on the HCF life improvement of an exhaust manifold considering stress gradient to reduce the crack creation due to thermal stresses in the exhaust manifold. For this purpose, first Solidworks software was used to model the exhaust manifold. Three Perimeter fins with 4 mm thickness were attached to the modified exhaust manifolds outlet section. Then ANSYS software was used to determine temperature and thermo-mechanical stress distribution of the exhaust manifold. Finally, in order to study the

HCF life of the exhaust manifold, the results were fed into the ANSYS nCode Design Life software. Most engine components have complicated geometries and contain different kind of notches. In fatigue life estimation of these components, the effects of notch-like features must be taken into account [18]. In this study, the notch effect is considered based on the stress gradient approach described in the FKM method.

2 METHODOLOGY

2.1. The Finite Element Model and Material Behavioral Model

The material employed for the exhaust manifold is the gray cast iron EN-JGL-250. Fatigue life prediction of each component needs the cyclic stress-strain distribution. Hot components of engines had complex geometry and loading, and the applying analytical methods for the detection of stress-strain distribution in them is impossible. Many researchers have used finite element method to obtain stress-strain distribution in geometrically complex components [6], [8], [11], [13].

The exhaust manifolds analyzed in this article are shown in “Fig. 1”. Three Perimeter fins with 4 mm thickness are attached to the modified exhaust manifold outlet section.

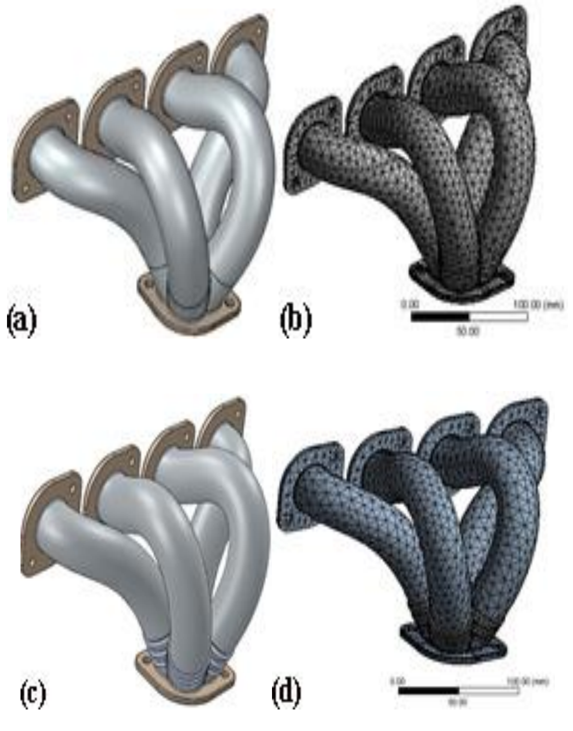

Fig. 1 (a): The exhaust manifold generated by SolidWorks, (b): Finite element model of the original exhaust manifold, (c): Modified exhaust manifold with fins attachment, (d): Finite element model of the modified exhaust manifold

The manifold is cast from gray iron with a thermal conductivity of 48 W/mm°C, a density of 7200 kg/m^3, a Young's modulus of 115 GPa, a Poisson's ratio of 0.26, and a coefficient of thermal expansion of 10×10^{-6} per °C. The three Perimeter fins are made of aluminum with a thermal conductivity of 167W/mm°C, a density of 2700 kg/m^3, a Young's modulus of 68.9 GPa and a Poisson's ratio of 0.33 [11], [13]. Ten bolts fasten the manifold to the cylinder head. The bolts are made from steel, with a Young's modulus of 207 GPa, a Poisson's ratio of 0.3, and a coefficient of thermal expansion of 13.8×10^{-6} per °C [17]. 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 [19]:

$$k_s \frac{\partial T}{\partial n} = h_s(T_s - T_\infty) + \varepsilon\sigma(T_s^4 - T_\infty^4) \quad (1)$$

For thermal fatigue evaluation, it is important to select and use an accurate model to describe the material cyclic mechanical behavior. The Lemaitre and Chaboche formulation are used to describe an elastoplastic cyclic behavior. The load criterion is defined by [20]:

$$f = f_y(\boldsymbol{\sigma} - X) - R \quad (2)$$

Both non-linear kinematic and isotropic hardening are used:

$$dX = \frac{2}{3} C d\varepsilon_p - DXdp \quad (3)$$

$$dR = b(Q - R)dp \quad (4)$$

$$X = \frac{C}{D} + [1 - \exp(-D\varepsilon_p)] \quad (5)$$

$$R = R_0 + Q[1 - \exp(-bp)] \quad (6)$$

$$\sigma = X + R \quad (7)$$

$$\sigma_u = \frac{C}{D} + Q + R \quad (8)$$

2.2. Stress Gradient Consideration Using FKM Method

Notch effect is the main detrimental factor on reducing fatigue life due to the existing of stress concentration near notch roots. Machine components usually contain stress raisers that are known as a notch. Due to high stress gradients around the notch root, there are more difficulties to solve the fatigue problem of such components compared to smooth specimens [18]. It is widely recognized that the stress gradient is of paramount importance for assessing fatigue strength in notched parts. [21]. The FKM method describes a method in which the fatigue strength of a material is increased by a factor based on the surface normal stress gradient and the strength and type of material. There are several approaches to estimate the fatigue notch factor, among which FKM is recommended by the authors. According to FKM method, the correction factor can be calculated in dependence of relative stress gradient as follows:

for $\overline{G}_\sigma \leq 0.1$

$$n_\sigma=1+\overline{G}_\sigma 10^{-(a_G-0.5+\frac{R_m}{b_G})} \tag{9}$$

For $0.1< \overline{G}_\sigma \leq 0.1$

$$n_\sigma=1+\sqrt{\overline{G}_\sigma}10^{-(a_G-0.5+\frac{R_m}{b_G})} \tag{10}$$

For $<1\overline{G}_\sigma \leq 10$

$$n_\sigma=1+\sqrt[4]{\overline{G}_\sigma}10^{-(a_G-0.5+\frac{R_m}{b_G})} \tag{11}$$

2.3. Model for TMF Life Prediction

For TMF, the damage coefficients per cycle can be described by a function with not only maximum stress and mean stress, but also maximum temperature and temperature range [22]:

$$\frac{d\mathbf{D}}{dN}=f(\sigma_{max}\sigma_{mean}T_{max}\Delta T) \tag{12}$$

Equation (12) is defined as bellows if $\sigma_{min}=0$ [22]:

$$(N_f)_{TMF}=\frac{(\sigma_u-\sigma_{max})[\frac{\sigma_{max}}{M_0 T_{max}\Delta T}]^{\beta(T_{max}\Delta T)}}{\alpha[\beta(T_{max}\Delta T)+1](\sigma_{max}-\sigma_1)} \tag{13}$$

The stress-based approach to fatigue is typically used for life prediction of components subject to high cycle fatigue, where stresses are mainly elastic. This approach emphasizes nominal stresses rather than local stresses. It uses the material stress-life curve and employs fatigue notch factors to account for stress concentrations, empirical modification factors for surface finish effects, and analytical Equations such as Goodman Equation to account for mean stress effects. Goodman criterion is used to evaluate the fatigue life of aluminum alloy piston [8], [23]. The Goodman Equation is given by Equation [7]:

$$\frac{\sigma_a}{\sigma_1}+\frac{\sigma_{mean}}{\sigma_u}=1 \tag{14}$$

2.4. Experimental 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. Tensile tests were conducted using a servo-hydraulic MTS 810 material machine (“Fig. 2”). 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.

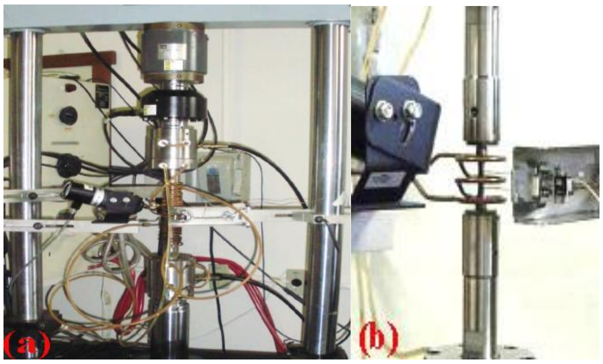

Fig. 2 (a): Material testing machine MTS 810, and (b): induction heater and extensometer.

3 RESULTS AND DISCUSSION

3.1. Experimental tensile tests results

Figure 3 depicts the gray cast iron EN-JGL-250 stress-strain curves at three temperatures (30, 500 and 700° C). There are several methods to insert the values of C and D into ANSYS software that one of them is entering yield stress at plastic strain using the tensile test [5]. The yield stress at plastic strain was extracted by means of the tensile tests results and entered into the ANSYS software.

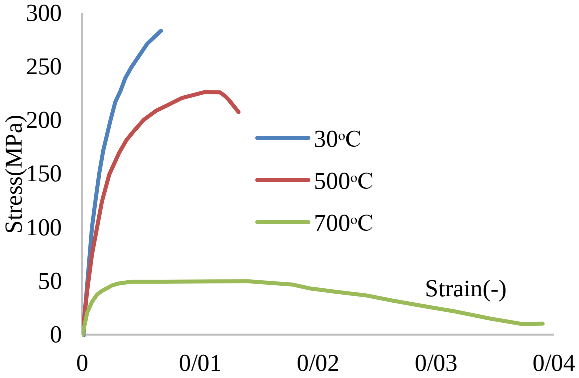

Fig. 3 Stress-strain behavior in tensile test of EN-JGL-250 at 30, 500 and 700°C.

3.2. Thermal Analysis

It is also important to evaluate the exhaust manifolds temperature field in order to detect the thermal stresses and fatigue life within allowable limit. Thus, the first step of a HCF 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], [4-6], [11], [13]. 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 are used at the flange surfaces attached to the cylinder head and exhaust manifold, respectively [11], [13], [17]. Contour results of the temperature distribution are given in “Fig. 4”. As expected, the temperature maximum is occurred in the confluence region. This corresponds to the results by [6], [10], [11], [13], [17].

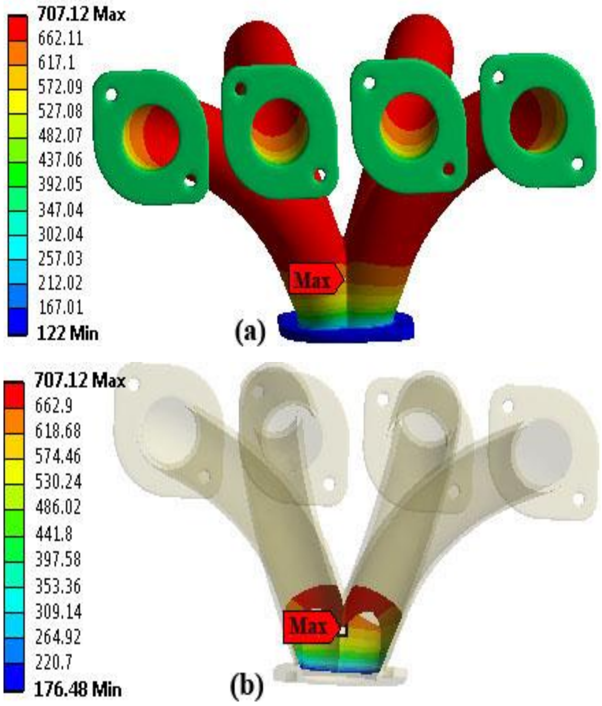

Fig. 4 The temperature distribution in the original exhaust manifold: (a): whole exhaust manifold, and (b): confluence area.

It is known that temperature elevation imposes significant adverse impact on fatigue [1], [5]. Contour results of the temperature distribution in the modified exhaust manifolds are shown in “Fig. 5”. The confluence area is a crucial area [1], [5]. The temperature gradient changes from 707.12°C to 176.48°C for the original exhaust manifolds. For the modified exhaust manifolds, this temperature gradient is lower due to the perimeter fins, the temperature changes from 675.96°C to 173.94°C. It means that maximum temperature of modified exhaust manifolds reduces up to 31.16° using the perimeter fins. This can lead to lower stress values in the modified exhaust manifolds. Thus, the fatigue lifetime can be improved [11].

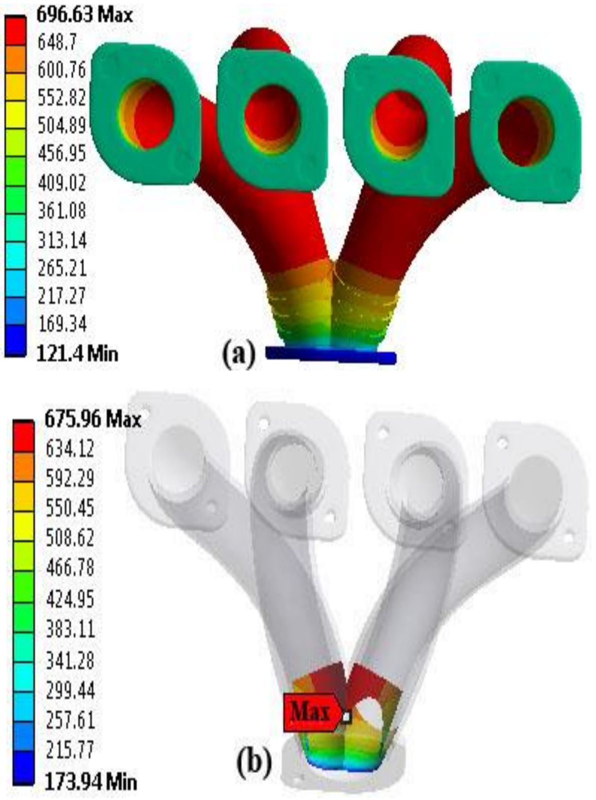

Fig. 5 The temperature distribution in the modified exhaust manifold: (a): whole exhaust manifold, and (b): confluence area.

3.2. Mechanical Analysis

The exhaust manifolds bear the mechanical stress and withstands the thermal stress due to the temperature fluctuations. Therefore, the analysis of thermo-mechanical coupling stress on the cylinder heads is needed [1-3], [5-6], [8]. The loads of the thermo-mechanical coupling stress analysis of the exhaust manifolds include gas pressure, bolt preload, thermal load calculated from thermal analysis [1], [5]. The analysis of the thermo-mechanical coupling stress is based on the results of the analysis of mechanical stress. The temperature distribution and the mechanical loads are taken into consideration at the same time. Import the calculated results of the exhaust manifolds temperature and impose the mechanical stress [1-3], [5-6], [8], [11], [13], [16-17]. Then finite element calculation is carried out and the results are studied. Von-Mises stress distribution at the end of the second stage is shown in “Fig. 6”.

Stress contour results for the modified exhaust manifolds are presented in “Fig. 7”. This Figure demonstrates that perimeter declines the stress distribution in the confluence area. The stress reduction value in the modified exhaust manifold is about 19 MPa which can lead to higher fatigue lifetimes in comparison to the original exhaust manifold.

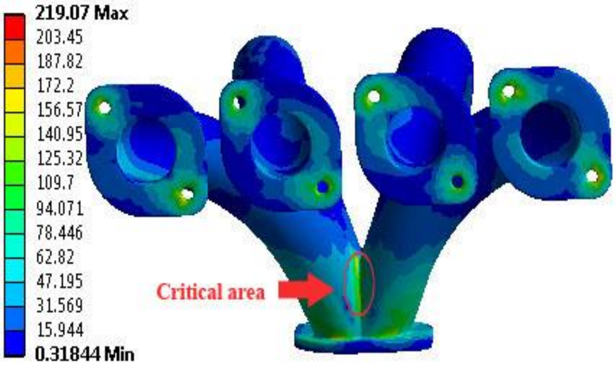

Fig. 6 The Von-Mises stress distribution in the original exhaust manifold.

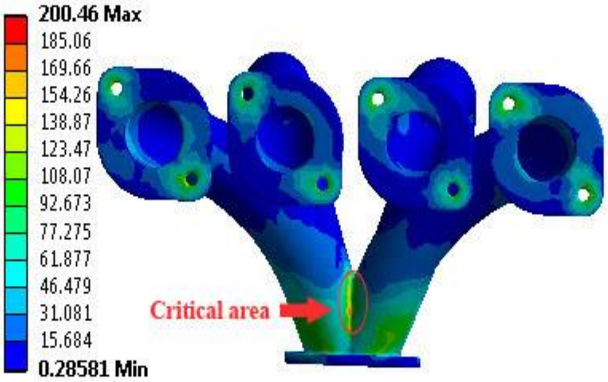

Fig. 7 The Von-Mises stress distribution in the modified exhaust manifold.

3.3. Verification of FEA Results

The numerical simulation results for the original and modified exhaust manifold piston are compared on "Table 1" with results found on previous work from the literature survey [11]. As it is observed from "Table 2", there is a good compromise between FEA results and data observed on the literature survey [23].

Table 1 Comparison of the FEA results and Source [11]

Original piston	Numerical simulation	Source [11]
Maximum temperature for the original manifold	707.12°C	705.1°C
Maximum temperature for the modified manifold	696.63°C	695.1°C
Maximum stress for the original manifold	219.07MPa	233.1MPa
Maximum stress for the modified manifold	200.46MPa	211.1MPa

3.4. HCF life prediction

It is necessary to carry out the thermo-mechanical fatigue checkout for the exhaust manifolds [1], [5], [11], [17]. For this purpose, fatigue tests are usually performed on the specific fatigue machine, but they are complex, high cost and time-consuming [11], [24]. In this paper, the HCF prediction, based on the Goodman Equation, is conducted to calculate the high cycle fatigue life instead the experimental fatigue tests. In order to study the fatigue life of the exhaust manifold based on HCF approach, the stresses histories were fed into the nCode Design Life software. Figures 8 and 9 represent the number of cycles to failure in the original and modified exhaust manifold, respectively. The results indicate that the number of cycles of failure for modified exhaust manifold is approximately 63% higher than the results obtained from the original exhaust manifolds.

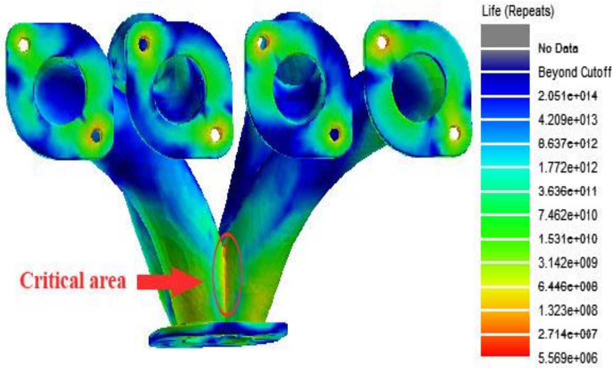

Fig. 8 The number of cycles to failure in the original exhaust manifold.

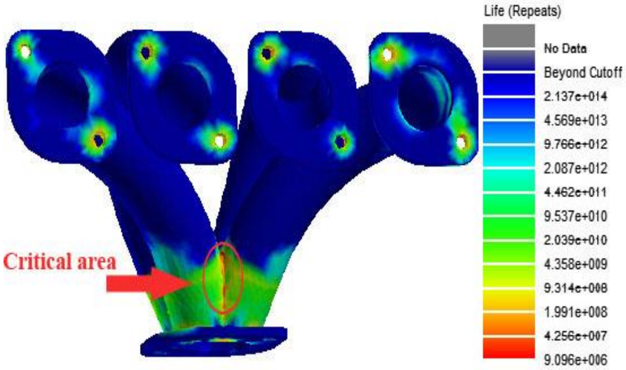

Fig. 9 The number of cycles to failure in the modified exhaust manifold.

As it has been observed in most thermal shock test, the exhaust manifold is broken like "Fig. 10". The review of "Fig. 4-9" reveals that results of FEA and HCF are corresponded with experimental tests carried out in references, and illustrate the exhaust manifolds cracked in this region.

Fig. 10 Hair-line crack in thermal shock test [25].

4 CONCLUSIONS

It is proven that exhaust manifolds are subjected to thermos-mechanical loading due to the thermal stress resulted from start-stop cycles and must be studied via FEA [11], [17]. The aim of this work is to evaluate the effect of fin attachment on the HCF life improvement of an exhaust manifold to reduce the crack creation due to thermal stresses in the exhaust manifold. The results of FEA showed that the temperature distribution in the modified exhaust manifolds dwindles approximately 31°C. Therefore, the exhaust manifolds withstand less temperature and HCF life will increase. The thermo-mechanical analysis proved that Von-Mises stress decreases about 19 MPa using the perimeter fins, which can lead to higher fatigue lifetime. HCF life results showed that the number of cycles of failure for modified exhaust manifold is approximately 63% higher in comparison to the original exhaust manifolds. Computer aided engineering plays an important role to find the weakness of An exhaust manifold layout at the early stage of the engine development.

5 NOMENCLATURE

k	Thermal conductivity
h_s	Convention heat transfer coefficient
T_s	Manifold temperature
T_∞	Air temperature
ε	Surface emissivity
σ	Stephan-Boltzmann constant
f	Plasticity threshold
f_y	Von Mises criteria
σ	Stress tensor
X	Non-linear kinematic tensor
R	Yield stress
ε_p	Plastic strain tensor
p	Accumulated plastic strain
Q	Material constant
b	Material constant
C	Material constant
D	Material constant
R_0	Material constant
σ_u	Ultimate uniaxial stress
n_σ	Correction factor
$\overline{G}_\sigma$	Relative stress gradient
a_G	Material constant
b_G	Material constant
D	Damage variable
N	Cycle
σ_{max}	Maximum stress
σ_{mean}	Mean stress
T_{max}	Maximum temperature
ΔT	Temperature range
$(N_f)_{TMF}$	Cycle to fracture of TMF
σ_1	Fatigue limit
σ_a	Alternating stress

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