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Low cycle fatigue life prediction of an engine exhaust manifold

Hojjat Ashouri
Department of Mechanical Engineering, Yadegar-e-Imam Khomeini (RAH) Shahre-Rey Branch, Islamic Azad University, Tehran, Iran

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ABSTRACT

This paper presents low cycle fatigue (LCF) life prediction of an engine exhaust manifold. First Solidworks software was used to model the exhaust manifolds. Then Ansys Workbench software was used to determine stress and fatigue life based on Morrow and Smith-Watson-Topper (SWT) approaches. Thermal fatigue (TMF) of the engine components easily happens due to excessive temperature gradient and thermal stress. Modern exhaust systems must withstand severe cyclic mechanical and thermal loads throughout the whole life cycle. The numerical results showed that the temperature and thermal stresses have the most critical values at the confluence region of the exhaust manifolds. This area was under low cycle fatigue. After several cycles the fatigue cracks will appear in this region. The results of the finite element analysis (FEA) correspond with the experimental tests, carried out in references, and illustrate the exhaust manifolds cracked in this region. Finite element (FE) simulation proved a close correlation between Morrow and SWT criterions results. The lifetime of this part can be determined through finite element analysis instead of experimental tests.

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1. Introduction

An exhaust manifold is an automotive component that collects the combustion gases from the cylinders of an internal combustion engine, directing them to the exhaust system of the vehicle [1, 2, 3]. They play an important role in the performance of an engine system [1, 4]. Automotive engine works under thermo-mechanical loading conditions. Working temperature increases up to 1000ºC from ambient temperature and thermal stress is prompted by temperature gradient. The temperature difference, which is the result of turning the engine on and off, begets TMF loads on the exhaust manifolds. This thermo-mechanical stresses is one of basic issues in automotive designing will lead to thermo-mechanical failure. Therefore, selection of materials is of paramount importance since they must have sufficient mechanical strength at high temperatures to be able to withstand cyclic stresses caused by heat [2, 5, 6].

High durability standards, low emissions, minimized vibration and heat dissipation during cold-starting, maximized heat dissipation in high temperature conditions to minimize catalyst ageing and minimizing mass in order to improve fuel economy are among the restrictions making the design of exhaust manifolds a complicated

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[*] Corresponding Author
Email Address: ashori1394@gmail.com

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task. Thus, detailed analysis and design are essential [2, 4, 7]. Due to complicated boundary conditions, there is the probability of plastic strain and the creation and growth of fatigue cracks in the exhaust manifolds. Therefore, this simulation and analysis of fatigue cracks in the design of exhaust manifolds is of paramount importance [3].

Numerous papers have been presented on analysis of stress and fatigue in exhaust manifolds. Delprete et al. predicted fatigue life of exhaust manifolds by finite element simulation via the several model of multiaxial damage and compared with experimental results. Their research proved an acceptable agreement between experimental and simulated results of the fatigue life of the exhaust manifolds [8]. Low and high cycle fatigue (HCF)life estimation of a turbocharged diesel engine exhaust manifolds was studied by Sissa and colleagues. Their research revealed that vibrational loadings cannot be neglected for correctly estimating the fatigue life of the turbocharged diesel engine exhaust manifolds [4]. Thermo-structure simulation of exhaust manifolds were carried out by Delprete and Rosso. Crucial locations in the finite element analysis were the same locations of crack initiation in the experimental conditions [9].

Wohrmann et al. optimized exhaust manifolds geometry. Their research after modification of exhaust manifolds geometry shows the simulated results of the number of cycles of crack initiation and the location of crack initiation are in accord with experimental results [10]. Heat transfer in the right-bank exhaust manifolds of a turbocharged V-6 diesel engine under steady state conditions was conducted by He et al. Their research proved a good agreement between experimental and simulated results of the gas temperature and heat flux at the outlet of the manifolds [11]. Thermal fatigue failure of the engine components easily happens due to excessive temperature gradient and thermal stress. The first fatigue cracks can be seen at the hottest spot of exhaust manifolds [12]. Gocmez and Deuster proposed a more comprehensive solution for exhaust manifold design. In their research, using the finite element method and constructing a virtual sampler instead of the actual sample, they investigated various reasons of fracture and failure of exhaust manifolds. They also simulated the effects of heat and oxidation, etc. on the exhaust manifolds [13].

Comparing temperature, strain and displacement distribution of exhaust manifolds proved that a close correlation between FEA and cell method results [8]. Santacreu et al. used chaboche model to investigate the elastic, plastic and viscous behavior of the exhaust manifolds. Their research uncovered the fact that viscous strain is significant and its amount is not negligible [2]. Thermo-mechanical analysis of exhaust manifolds of a turbocharged gasoline engine was performed by Chen et al. The simulated results indicate that predicted crack locations and leak area are in agreement with that from the engine durability test [5].

Zhein et al. analyzed unsteady heat transfer of exhaust manifolds. Their research showed a good agreement between strong and serial coupling method results [6]. Coupled CFD-FEA analysis of 6-cylinder diesel engine exhaust manifolds was studied by Vyas et al. A good agreement between experimental and simulated results of the temperature distribution was proved [14]. El-Sharkawy et al. investigated transient thermal analysis of exhaust manifolds. According to their study the experimental and simulated results of temperature match [15].

Thermo-mechanical fatigue of diesel engine exhaust manifolds was examined by Azevedo Cardoso and Claudio Andreatta. Their research refuted the possibility of failure in all spots [16]. Castro Güiza et al. did thermal fatigue fracture of exhaust manifolds. Their analysis indicated that some regions of the cylinder heads entered into yield region. Hence, fatigue cracks appear in them [17]. In another attempt, Low/high cycle fatigue and thermo-mechanical fatigue of exhaust manifolds were examined by Li et al. A good correlation between experimental and simulated results was shown [7].

Ekström et al. investigated the effects of thermal barrier coatings (TBCs) on temperature distribution in the exhaust manifold of a diesel engine. Their research uncovered the fact that thermal barrier coatings reduce the temperature distribution in the substrate of the exhaust manifold about 219°F[18].

According to the introduction, due to the lack of information on the behavior of hardening, softening and viscosity of materials the analysis of exhaust manifolds is mostly based on simple models of material behavior like elastic-plastic and the effects of viscosity and creep of exhaust manifolds are less taken into consideration. In this paper, TMF analysis of the exhaust manifold is done by using finite element method and Ansys software to calculate the stresses and then fatigue life by using Morrow and SWT theories.

2. The material and its behavioral model

In this study the gray cast iron alloy of Silicon-Manganese has been used to simulate the thermo-mechanical behavior. The alloy is known as EN-JGL-250 gray cast iron which is applied in exhaust manifolds.

Kinematic hardening has both linear and nonlinear isotropic/kinematic model. The first model can be used with Mises or Hill yield surface while the second one can only be used with the Mises yield surface and it is the most accurate and comprehensive model to examine some issues with cyclic loading including cylinder heads of engines. The kinematic hardening model assumes that the yield surface, proportional to the value of α, moves as back stress in yield zone but it does not deform [19]:

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

Where C is kinematic hardening modulus, $\dot{C}$ is the exchange rate of C in temperature and $\dot{\bar{\varepsilon}}^{PL}$ is the rate of equivalent plastic strain. In this model σ^{0} (the size of the yield surface) remains constant. In other words, σ^{0} is always equal to σ_{0} (that is yield stress in zero plastic strain) remain constant. Nonlinear isotropic/kinematic hardening model includes motion of yield surface proportional to the value of α in stress zone and also changes in the size of yield surface is proportional to the plastic strain [19]. This model has been extracted from Chaboche experience [20, 21]. In order to introduce this model a nonlinear term is added to equation (1) to indicate the size of yield surface [19]:

$$\dot{\alpha}=C\frac{1}{\sigma^{0}}(\sigma_{ij}-\alpha_{ij})\dot{\bar{\varepsilon}}^{PL}-\gamma_{ij}\dot{\bar{\varepsilon}}^{PL}+\frac{1}{C}\dot{C}\alpha_{ij} \quad (2)$$

Where C and γ are material constants. Heat transfer in engine exhaust manifolds is governed by three effects: conduction through the metal, convection from the hot exhaust gases, and radiative exchange between different parts of the metal surface [7, 8, 22].

Heat transfer by conduction per unit area per unit time, $\dot{q}$, in steady situation is given by Fourier law [22]:

$$\dot{q}=-k\nabla T \quad (3)$$

Where k is the thermal conductivity and ∇T is temperature difference. Heat loss due to thermal radiation between the manifold surface and environment is modeled by the standard Stefan–Boltzmann relation [22, 23]:

$$\dot{q}=\varepsilon\sigma(T_{g}^{4}-T_{a}^{4}) \quad (4)$$

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 is mainly due to forced convection and is strongly dependent on the gas flow dynamics and the manifold geometry. Chirchil and Chu law is used in order to consider heat convection from manifold surface to ambient air, the equation of which is following [11]:

$$Nu=(0.6+(\frac{0.387Ra^{\frac{1}{6}}}{(1+\left(\frac{0.599}{Pr}\right)^{\frac{9}{16}})^{\frac{8}{27}}}))^{2} \quad (5)$$

Where Nu is Nusselt number, Ra is Rayleigh number and Pr is are Prandtl number.

3. Models for thermo-mechanical life prediction

TMF is the case of fatigue failure due to simultaneous thermal and mechanical loading. The life prediction of TMF loading cases has received considerable attention in recent years mainly in engine parts. The fluctuation of complex thermal and mechanical strains is usually determinant for fatigue life of machine parts. Thermo-mechanical and low cycle fatigue can show a lot of similarity, mainly because of the presence of cyclic plastic strain. The cyclic thermal load occurs by nature in a small number of cycles, but the stresses generated by the restrained thermal expansion may be far beyond the elastic limit. In engine parts the superposition of a LCF/TMF effect due to start-stop cycles and a HCF effect due to the combustion cycle is to be observed [2, 5, 6].

For some materials such as gray cast iron, crack nucleation and/or crack growth is along the maximum tensile stress or strain planes. In this case, the SWT parameter can be used as the damage model, where governing parameters are the maximum principal strain amplitude, ε_a, and maximum normal stress acting on maximum principal strain amplitude plane, $\sigma_{n,max}$. The equation is given by:

$$E\varepsilon_{a}\sigma_{n,max}=(\sigma_{f}^{'})^{2}*(2N_{f})^{b}+(E\sigma_{f}^{'}\varepsilon_{f}^{'})*(2N_{f})^{b+c} \quad (6)$$

Where $\sigma_{f}^{'}$ 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, $\varepsilon_{f}^{'}$ is the fatigue strength coefficient and c is the fatigue ductility exponent fatigue ductility exponent.

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The fatigue damage estimation has been performed according to LCF approach, by using the Morrow's equation. Morrow and SWT equations are two main methods of strain based approach applied widely in engine industry. These methods have been used to handle mean stress effects. Fatigue life is estimated with Morrow relationship [24 ,25]:

$$\Delta\varepsilon = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{\sigma_f^{\prime} - \sigma_{mean}}{E}(2N_f)^b + \varepsilon_f^{\prime}(2N_f)^c \quad (7)$$

Where $\Delta\varepsilon$ is the strain amplitude and σ_{mean} is the mean stress.

4. The finite element model and material properties

TMF analysis of each component needs the cyclic stress-strain distribution. Hot components of engines have complex geometry and loading, and the application of 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 the geometrically complex components [26]. The exhaust manifolds analyzed in this article are shown in Fig. 1.

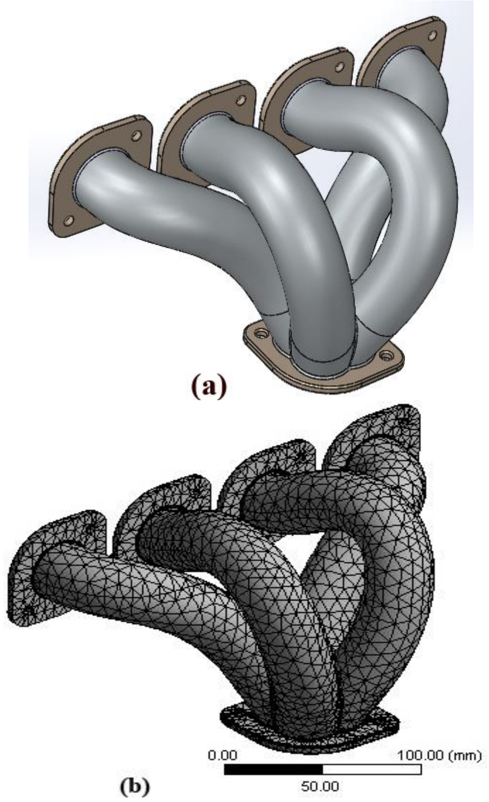

Figure 1: a) The exhaust manifold generated by SolidWorks and b) Finite element model of the exhaust manifold

Exhaust manifolds consists of four tube with four flanges, bolted with eight bolts to the engine cylinder head. The manifold is cast from gray iron with 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. Exhaust manifolds are modeled with three-dimensional continuum elements. The model consists of 23457 elements (Tet10) for improving the accuracy and acceptability of the obtained results.

5. Analysis procedure

Life prediction of the exhaust manifolds is as follows:

1- subject the exhaust manifolds to the steady-state operating temperature distribution
2- Gas pressure and temperature distribution data are used to simulate thermal stress analysis
3- Prediction of the TMF life using Morrow and SWT theories

6. Results and Discussion

6.1. Thermal Analysis

Thermal analysis includes the simulation of working condition in steady and transient state(Alkidas et al., 2004; Delprete and Rosso, 2005). In these conditions, exhaust manifolds are subject to thermal exchange phenomena such as conduction, convection, radiation(Delprete and Rosso, 2005; Li et al., 2017). Thermal analysis goal is the evaluation of temperature distribution in exhaust manifolds(Santacreu et al., 2012; Chen et al., 2014).

Temperature peak and temperature distribution of exhaust manifolds are dominant factors in TMF durability assessment, since the thermal fatigue crack and gasket leakage can be initiated by thermal deformation due to spatial and temporal temperature variations(Chen et al., 2014; Yan et al, 2014). The ability to accurately predict skin temperature for vehicle exhaust system is very important for a robust/durable design of the vehicle exhaust system(Meda et al., 2012; Zhien et al., 2014).

Accurate prediction of the temperature of the engine is very crucial and increases the precision of the FEA results. As the accuracy of thermal analysis increases the accuracy of mechanical analysis and fatigue life estimation rises(Gocmez and Deuster, 2009; Chen et al., 2014).

The manifolds are cast from gray cast iron with a thermal conductivity of 48 W/mm°C, a density of 7200 kg/m^3, and a specific heat of 460 J/kg°C. The manifolds begin the analysis with an initial temperature of 20°C. The Stefan Boltzmann constant is taken as 5.669×10^{-14} W/mm^{2}K^4 and

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absolute zero is set at 273.15°C below zero. The surface emissivity of gray cast iron is taken as a constant value of 0.77.

The hot exhaust gases create a heat flux applied to the interior tube surfaces. In this article this effect is modeled using a surface-based film condition, with a constant temperature of 816°C and a film condition of $500*10^{-6}$ W/mm^2°C. A temperature boundary condition of 355°C is applied at the flange surfaces attached to the cylinder head, and a temperature boundary condition of 122°C is applied at the flange surfaces attached to the exhaust. In this analysis one thermal cycle is applied to obtain a steady-state thermal cycle. Each thermal cycle involves two steps: heating the exhaust manifolds to the maximum operating temperature and cooling it to the minimum operating temperature.

The temperature distribution of exhaust manifolds is exhibited in Fig. 2. Similarly, temperature was high in most regions, especially in the junction of four pipes(confluence region) and the maximum reached 708.65°C. This corresponds to the results by Sissaa et al. (2014).

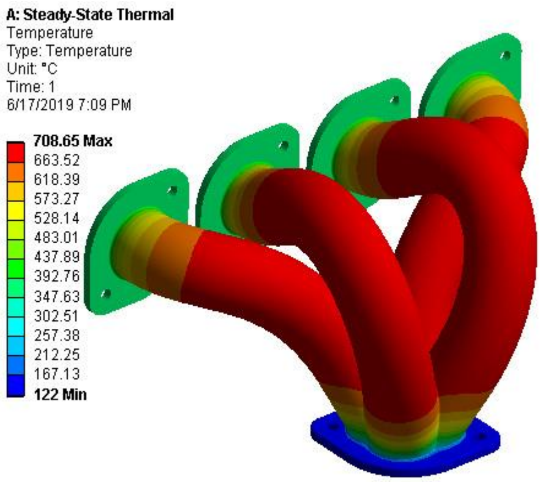

Figure 2: The temperature distribution in the exhaust manifold

Thermal loading has a considerable effect on the fatigue life and the temperature field identifies critical regions. Crack initiation is due to the changes in the temperature field(Chen et al., 2014; Azevedo Cardoso and Claudio Andreatta, 2016).

6.2. Mechanical analysis

Engine exhaust manifolds are commonly subject to severe thermal cycles during operation and upon shutdown. Thermal expansion and contraction of the exhaust manifolds is constrained by their interaction with the engine head to which it is bolted. These constraints govern the thermo-mechanical fatigue life of the exhaust manifolds(Mamiya et al., 2002; Azevedo Cardoso and Claudio Andreatta, 2016).

The cyclic thermal loads are applied in the second analysis step. It is assumed that the exhaust manifolds are securely fixed to a stiff and bulky engine cylinder head, so the flange surfaces is constrained in the direction normal to the cylinder head but are free to move in the two lateral directions to account for thermal expansion. Another boundary condition is the gas pressure of the exhaust manifolds. This pressure is applied as a mechanical load on the inner surface of the manifold tubes.

Von-Mises stress distribution at the end of the third stage is shown in Fig. 3. The maximum value of Von-Mises stress in the exhaust manifolds is calculated 232.25 Mpa. Comparing this result to the yield stress of the exhaust manifolds can be a criterion for the crack initiation. This can lead to the crack initiation. The maximum Von-Mises stress was at the intersection of tubes(confluence area) of the exhaust manifolds, except for the areas around the screws where there was stress concentration. Based on the source (Dong et al., 2009; Chen et al., 2014), the first fatigue cracks can be seen at the hottest spot of cylinder heads (Figure 2). This region is also located in the confluence region.

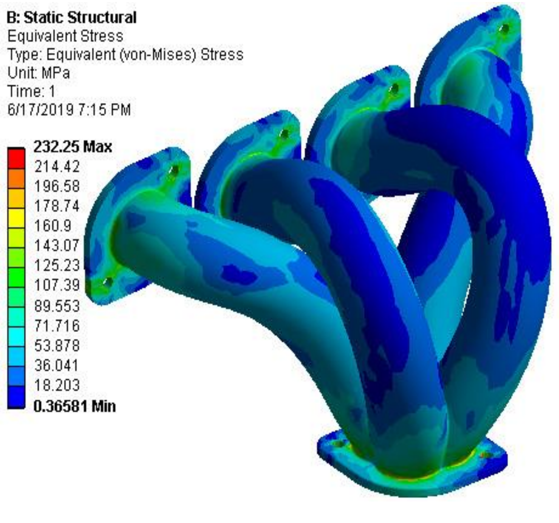

Figure 3: The Von-Mises stress distribution at the end of the third stage of loading

Equivalent plastic strain(PEEQ) distribution is depicted in Fig. 4. PEEQ is greater than zero, indicating that the material is currently yielding. PEEQ is specified as part of plasticity behavior definition; the hazardous position can be found where the PEEQ maximum is. As stated in sources (Yan et al., 2014; Liu et al., 2015, Castro Güiza et al., 2017) the initiation of fatigue cracks in exhaust manifolds occurs where plastic strain happens because of thermo-mechanical loads.

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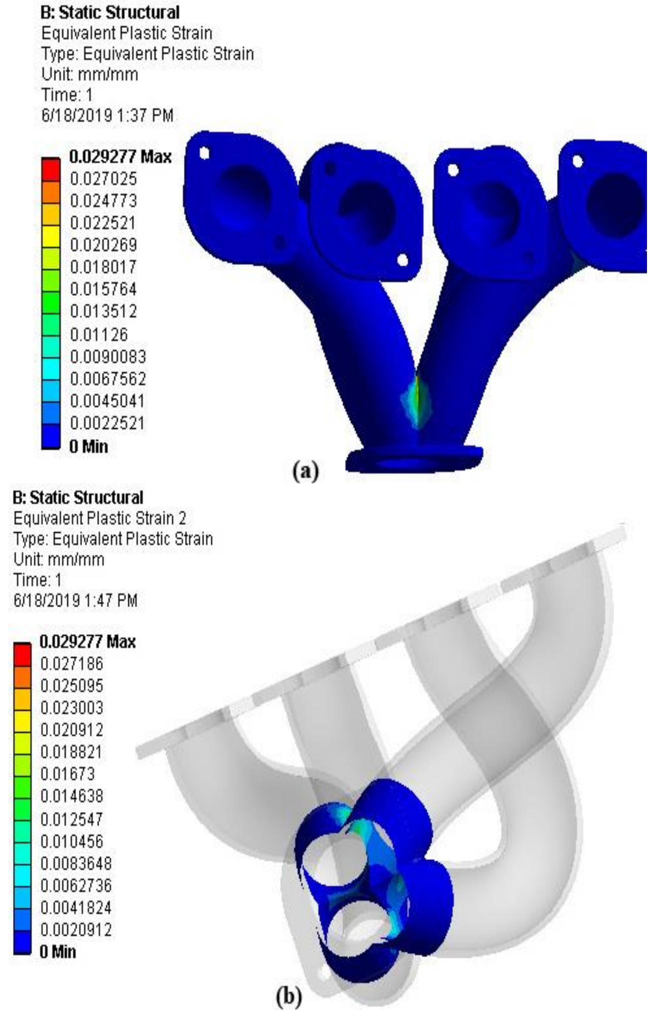

Figure 4: The equivalent plastic strain distribution in the : a) finite element model and b) confluence area

6.3. Low cycle Life prediction

Energy based method can easily and accurately estimate lifetime in multiaxial loading conditions but experimental results show that effect of mean stress have not been considered well for gray cast irons (Trampert et al., 2006). Therefore energy based approaches have not been used for lifetime prediction. Morrow and SWT equations have been shown to correlate mean stress effects(Stephens et al., 2001; Lee et al., 2005). As it has been observed in most thermal shock test, the exhaust manifold is broken like Fig. 5. This is because of the maximum principal strain on the critical element s which is shown in Figure 6 resulted from Ansys software at high temperature of the manifolds. The review of Figs. 2-6 reveals that results of FEA corresponds with experimental tests.

Figure 5: The cracked exhaust manifold

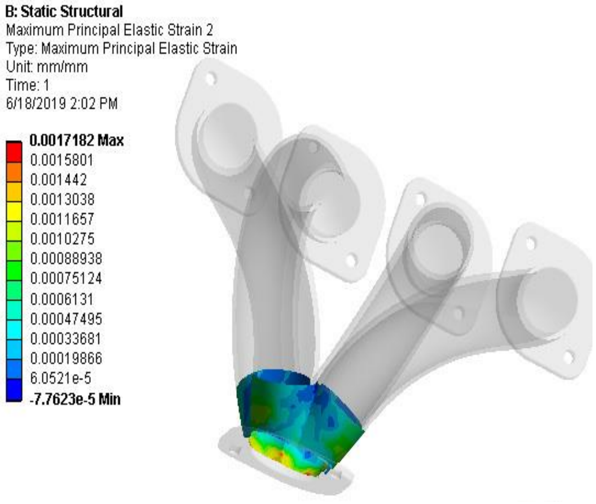

Figure 6: The maximum principal strain on the critical elements

Considering the value of infinite life as 1e9, the life is evaluated in ANSYS Workbench SWT and Morrow strain life approaches. Fig. 7 represents the number of cycles to failure based on SWT criterion. As it can be seen from this Figure, minimum life (12848 cycles) has been determined at the critical zones of the exhaust manifolds. In Fig. 8, the number of cycles to failure based on Morrow equation is shown. Minimum life (14401 cycles) has been predicted at the critical areas of the exhaust manifolds, as shown in Fig. 8. As it's shown in Figs. 7 and 8, a good agreement between Morrow and SWT approaches results. As it can be seen from s Figs. 7 and 8, the number of cycles to failure in the critical areas is under 10^4 or 10^5 which imposes low cycle fatigue for the manifold material(Stephens et al., 2001; Lee et al., 2005).

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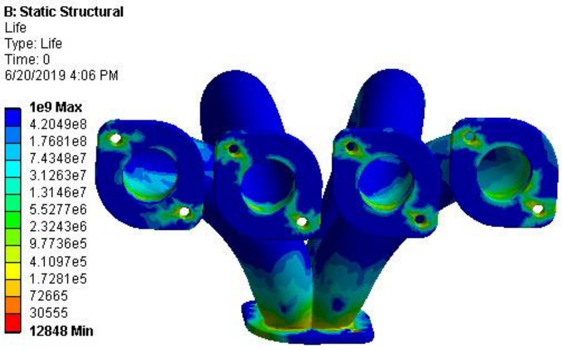

Figure 7: The number of cycles to failure based on SWT equation

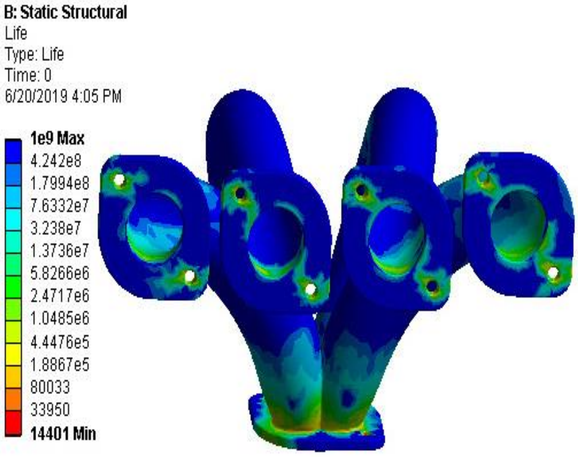

Figure 8: The number of cycles to failure based on Morrow equation

Figs. 9 and 10 indicate the factor of safety (FS) with respect to a fatigue failure at a given design life. This value depends between the minimum safe zones (0) to maximum safe zones (15). As it can be seen from these figures, minimum safety of the design (0.16472 and 0.16453) designates the critical zones. The area where the minimum FS occur is where the least life is predicted. The value of FS less than 1 indicates that the design will fail before the infinite life.

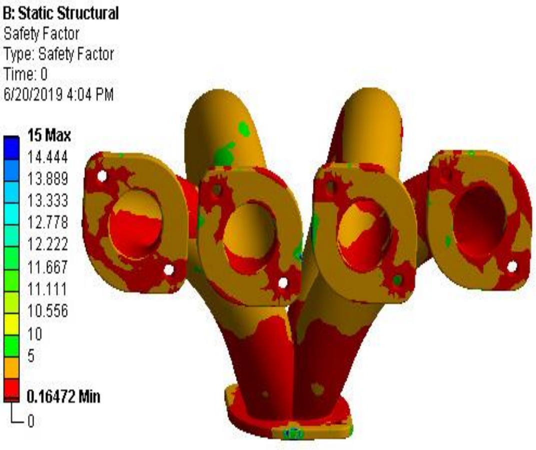

Figure 9: The factor of safety based on Morrow equation

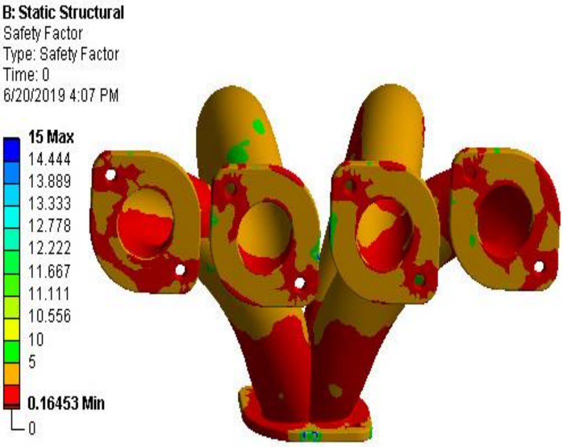

Figure 10: The factor of safety based on SWT equation

7. Conclusion

In this study low cycle fatigue life prediction of exhaust manifolds is studied by using SWT and Morrow strain life approaches. Finite element analysis provides accurate and reliable prediction of temperature and fatigue life results in the exhaust manifolds. The results of the thermo-mechanical analysis indicated that the maximum temperature and stress occurred in the confluence area. The maximum value of Von-Mises stress in the exhaust manifolds was calculated 232.25 Mpa. Comparing this result to the yield stress of the exhaust manifolds can be a criterion for the crack initiation. The Obtained FEA results correspond with the experimental tests, carried out in references, and illustrate the exhaust manifolds cracked in this region. The results of the Finite element analysis proved that confluence zone is under low cycle fatigue. After several cycles the fatigue cracks will appear in this region. The lifetime of this part can be determined through finite element analysis instead of experimental tests. The area where the minimum FS occurred is where the minimum life is predicted. FE simulation showed a good agreement between Morrow and SWT approaches results. Computer aided engineering plays an important role to find the weakness of an exhaust manifold layout at the early stage of the engine development. In order to prevent exhaust manifolds cracking it is recommended to modify geometry of material in crucial parts. TBC might also be used in the regions which not only reduce temperature, but also increase the fatigue life of exhaust manifolds. Since they reduce thermal stress, fatigue life of the exhaust manifolds grows.

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