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Evaluation of Thermal Barrier Coating in Low Cycle Fatigue Life for Exhaust Manifold

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Abstract

This paper presents low cycle fatigue (LCF) life prediction of a coated and uncoated exhaust manifolds. First Solidworks software was used to model the exhaust manifolds. A thermal barrier coating system was applied on the tubes c of the exhaust manifolds, consists of two-layer systems: a ceramic top coat (TC), made of yttria stabilized zirconia (YSZ), ZrO2-8%Y2O3 and also a metallic bond coat (BC), made of NiCrAlY. The temperature-dependent of material parameters was considered in order to increase the accuracy of LCF life results. Then Ansys Workbench software was used to determine stress and fatigue life based on Morrow and Smith-Watson-Topper (SWT) approaches. Thermal fatigue failure 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 results of finite element analysis (FEA) showed that the thermal barrier coating system reduces the temperature about 29°C because of its lower thermal conductivity. As a result, the exhaust manifolds tolerates lower temperature and fatigue life will increase. The results of thermo-mechanical analysis indicated that the stress in the coated exhaust manifolds decreased approximately 25 MPa for the sake of depletion of temperature gradient which can lead to higher fatigue lifetime. The results of LCF proved that the number of cycles of failure for coated exhaust manifold is approximately in the order 2-fold longer, than the results obtained from the uncoated exhaust manifolds.

Keywords: Thermo-mechanical fatigue, Finite element analysis, Exhaust manifolds and Confluence cracks

1- Introduction

The purpose of exhaust manifold system is to collect the gas exhausted from the cylinder head and send it to external ambient. As the manifold is connected to the cylinder head, the high temperatures in combustion chambers are transmitted to exhaust manifold[1,2,3]. The steady rise of engine power leads to higher operating temperatures within the exhaust manifold, which then undergoes thermo-mechanical fatigue(TMF) produced by cyclical increases and decreases of temperature. The manifold suffers from relatively high operating temperature, which can lead to significant thermal expansion. Thermal expansion is restricted in some regions due to the complex geometry of the manifold.

Therefore, expansion causes significant thermal stress, which may result in crack damage[2,5,6]. 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].

The emissions regulations for engines are becoming increasingly restrictive in order to limit the environmental and health effects from exhaust gases and particles. By increasing the specific power output of diesel engines, the fuel efficiency is improved and emissions greatly reduced [4,7]. As a result, exhaust manifolds and their surrounding components will experience higher temperatures as the engine efficiency is increased. Thus, it is of high interest to reduce the material temperature in the manifold in order to increase the lifetime of the components. This can be achieved by applying a thermal barrier coating (TBC) onto the material [8]. A typical TBC system consists of the substrate, metallic bond coat, mostly made of NiCrAlY, and ceramic top coat, mostly Yttrium stabilized Zirconium with composition $ZrO2-8\%Y2O3$. They offer potential for raising the engine operating temperature while enabling the substrate to experience a reduced temperature due to the temperature gradient across the outer ceramic TBC[9,10]. Increased engine temperature results in increased power efficiency and lower levels of greenhouse gas emissions. In addition, higher working temperature would cause a decrease on CO emissions because it has been concluded that CO reactions are dependent on temperature[11]. Moreover, TBC can cause remarkable decrease in substrate temperature. Therefore, due to the less thermal gradient in substrate, considerable increase in fatigue life is anticipated [9].

Numerous papers have been presented on analysis of stress and fatigue in exhaust manifolds. Low and high cycle fatigue 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]. Szmytka et al. did Thermo-mechanical fatigue of exhaust manifolds. The maximum stress, the same as maximum temperature, occurred in the upper zone of the structure near the turbocharger flange and in the manifold inner skin [12]. Benoit et al. predicted fatigue life of exhaust manifolds by finite element simulation via the energy model of damage. Confluence region was crucial area. The first fatigue cracks can be seen in this area [13]. Thermo-mechanical fatigue simulation of manifolds was studied by Ashouri. 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 the cyclic tensile and compressive stress and then is under low cycle fatigue [14].

Salehnejad et al. established the finite element method and critical fracture toughness for the failure analysis of an exhaust manifold. Their research refuted the possibility of failure in all spots [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 50°C,which is important for improving the fatigue life of exhaust manifold [8]. Comparing temperature distribution of coated pistons in a gasoline engine proved that YSZ is the best coating for the pistons to reduce unburned hydrocarbons [18].

Ashouri investigated the effect of thermal barrier coating on temperature distribution and the stress in cylinder head of a diesel engine. The results of his study disclosed that thermal barrier coatings decrease distribution of temperature and stress in the substrate of cylinder head, hence, the fatigue life of cylinder head increases [9]. Thermo-mechanical analysis of coated cylinder heads of a diesel engine was the subject of another study by Rezvani rad et al. They illustrated that the temperature of the substrate reduced up to 80°C when the TBC system was used. Also, the Von-Mises stress decreased about 20MPa by using the TBC system [19].

Quazi and Parashar studied the effect of thermal barrier coating on performance and emissions of off road vehicle. Their experiments proved that zirconium oxide is appropriate coating for enhancing specific fuel consumption and thermal barrier coatings reduce unburned hydrocarbons and carbon monoxide [20].

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. viscous properties in coating layers occur at higher temperatures more than 600°C [21]. Therefore, viscosity behavior should also be taken into accounted. In addition, few studies have been conducted on the effect of thermal barrier coating on distribution of temperature, stress and fatigue of exhaust manifolds.

It should be noted that using time-dependent of material properties for substrate would increase the accuracy of TMF results [10]. Therefore the effect of time-dependent properties for exhaust manifold, is also considered in this work.

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 as following equation shows [21]:

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

Where C is kinematic hardening modulus, $\dot{C}$ is of exchange rate of C in temperature and $\bar{\dot{\varepsilon}}^{PL}$ 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 [21]. This model has been extracted from Chaboche experience [22, 23]. In order to introduce this model a nonlinear term is added to equation (1) to indicate the size of yield surface as following equation shows: [19]:

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

Where γ is material constant. 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 [7,24]. Heat transfer by conduction per unit area per unit time, $\dot{q}$, in steady situation is given by Fourier law [24]:

$$\dot{q}=-k\nabla T \tag{3}$$

Heat loss due to thermal radiation between the manifold surface and environment is modeled by the standard Stefan–Boltzmann relation [24]:

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

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 [25]:

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

3- Models for TMF life prediction

In the real engineering world, engine components mostly operate under complex thermal-mechanical loading conditions where temperature and mechanical loads change simultaneously with time such as during engine start up and shutdown. The existence of thermal gradients due to uneven heat transfer by material and structural design may cause complex loading situations between thermal expansion and mechanical constraints and loads. Therefore, understanding and predicting TMF behavior has gained considerable practical significance with respect to component life prediction. An initial thermal loading of exhaust manifolds can cause the material to exceed the yield stress in large areas of the exhaust manifold. Cyclic temperature loading causes a few areas to exhibit local cyclic plastic straining of the material, which may cause a crack initiation[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:

$$E\varepsilon_a\sigma_{n,max}=(\sigma_f^{'})^{2}*(2N_f)^{b}+(E\sigma_f^{'}\varepsilon_f^{'})*(2N_f)^{b+c} \tag{6}$$

Where $\sigma_f^{'}$ is the fatigue strength coefficient, E is the modulus of elasticity, $2N_f$ is the number de 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.

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 [26 ,27]:

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

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 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 of geometrically complex components [14]. The exhaust manifolds analyzed in this article are shown in Fig. 1.

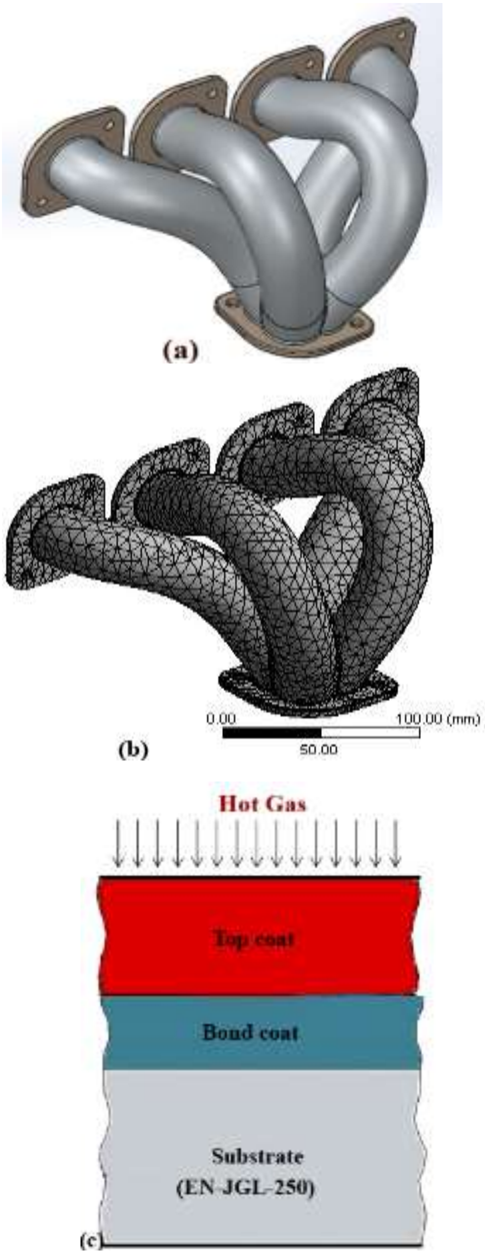

Fig. 1. (a) The exhaust manifold generated by SolidWorks, (b) Finite element model of the exhaust manifold and (c) TBC system

Exhaust manifolds consists of a four tube exhaust manifolds with f our 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- Result and Discussion

6-1- Thermal Analysis

The first step of the TMF is a transient thermal analysis with the aim to compute the temperature distribution on the components. Main loads acting on the manifold structure are temperature field. Thermal analysis goal is the evaluation of temperature distribution in exhaust manifolds [7,14]. 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 [5,14].

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^2K^4 and 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. In this research, the composition of TC is ZrO2–8 wt.%Y2O3 and that of BC is NiCrAlY. The thicknesses of BC and TC layers are considered as 135 µm and 380 µm, respectively. 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 when the exhaust manifolds are heated to its peak value is shown in Figure 2. It is maximized in the confluence region when there are no coating layers. This corresponds to the results by Sissaa et al. (2014) and Ashouri (2018).

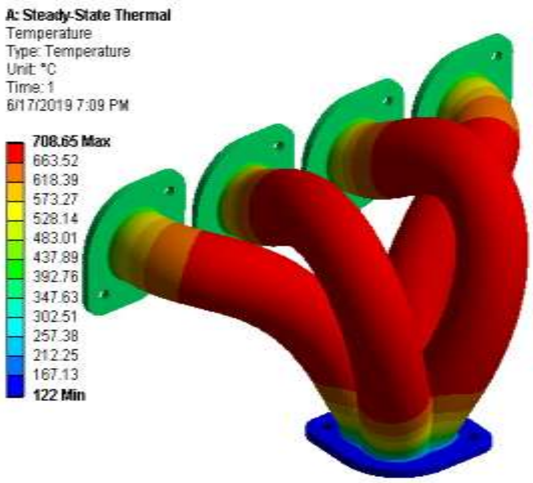

Fig. 2. The temperature distribution in the uncoated exhaust manifold

Thermal loading has a considerable effect on the fatigue life and the temperature field identifies critical regions [4,14]. Contour results of the temperature distribution in the coated exhaust manifolds are shown in Figure 3. This figure shows that although surface temperature of the ceramic layer of coated exhaust manifolds is about 61°C(from 769.56°C to 708.65°C higher than the exhaust manifold without coating, thermal barrier coating system reduces surface temperature of the substrate of coated exhaust manifolds about 29°C(from 708.65°C to 679.71°C), which is not much. In this example, the benefit of the TBC appears to be limited. However, a relatively small decrease in temperature can have a large impact on the fatigue life[8].

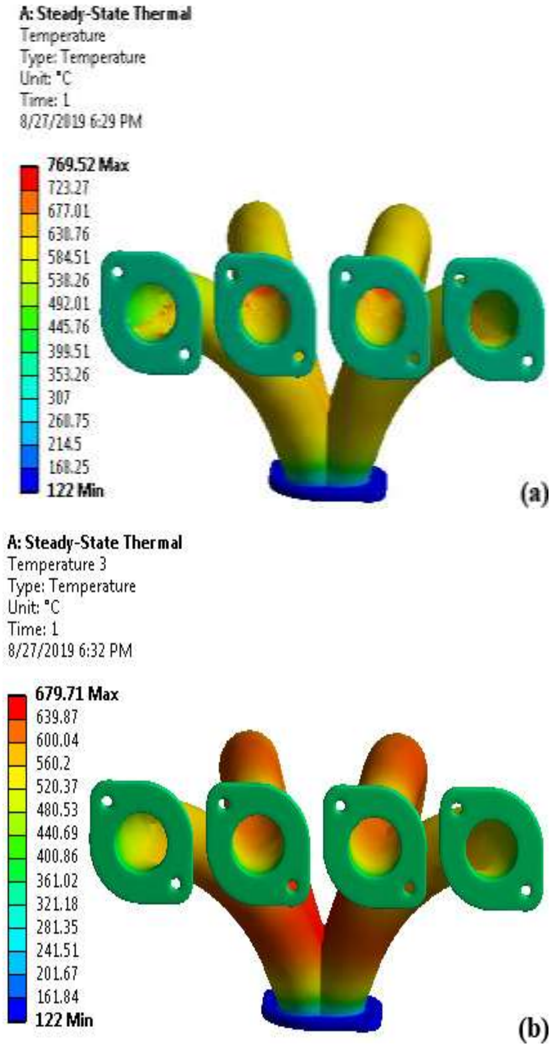

Fig. 3. The temperature distribution in the coated exhaust manifold: (a) without TBC and (b) with TBC

Given that the main task of thermal barrier coatings is preventing heat transfer to the substrate, thermal insulation and low thermal conductivity are among the most important factors in assessing the performance of these coatings and their practical development. That means insulating the substrate against high temperatures. In other words, using the thermal barrier coatings, reduce heat transfer to the substrate keeping it at lower temperature [28]. Therefore, the engine can bear higher temperature leading to increase of its efficiency. This helps engine longevity and cuts maintenance costs [29].

6-2- Mechanical Analysis

temperatures calculated by the previous thermal analysis have been imported in the structural model as thermal loads. Fatigue fractures in manifolds are thought to result from low cycle fatigue of constant strain due to repetition of thermal stress[14].

Material non-linearity is taken into account. Actual boundary conditions are represented by constraints and contacts between components.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 second stage is shown in Fig. 4. 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 leads 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. This corresponds to the results by Ashouri (2018). Based on the source [5] the first fatigue cracks can be seen at the hottest spot of exhaust manifolds (Figure 2). This region is also located in the confluence region.

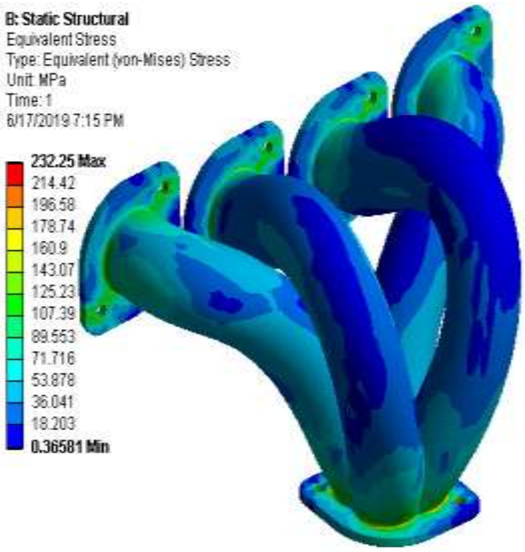

Fig. 4. The Von-Mises stress distribution in the uncoated exhaust manifolds

Stress contour results for the coated exhaust manifolds are presented in Figure 5.

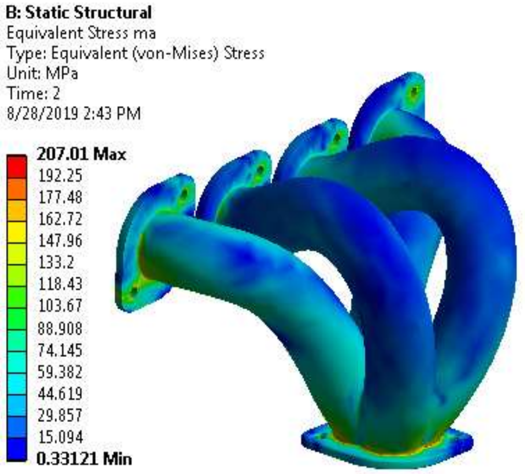

Fig. 5. The Von-Mises stress distribution in the coated exhaust manifolds

Figure 5 demonstrates that thermal barrier coating system declines the stress distribution in the confluence area. The stress reduction value in the coated exhaust manifold is about 25 MPa which can lead to higher fatigue lifetimes in comparison to the uncoated exhaust manifold.

6-3- Low cycle Life prediction

The start-stop temperature change produces high thermal gradients and thus high thermal stresses and strains which may lead to failure in a low number of cycles [30,31]. 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 [32]. Therefore energy based approaches have not been used for lifetime prediction. Morrow and SWT equations have been shown to correlate mean stress effects[26,27].

Considering the value of infinite life as 1e9, the life is evaluated in ANSYS Workbench with SWT and Morrow strain life approaches. Figs 6 and 7 represents the number of cycles to failure based on SWT criterion for coated and uncoated exhaust manifolds.

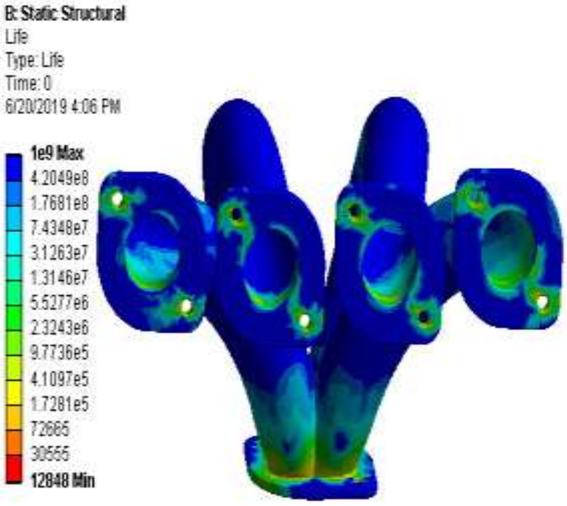

Fig. 6. The number of cycles to failure based on SWT equation for uncoated exhaust manifolds

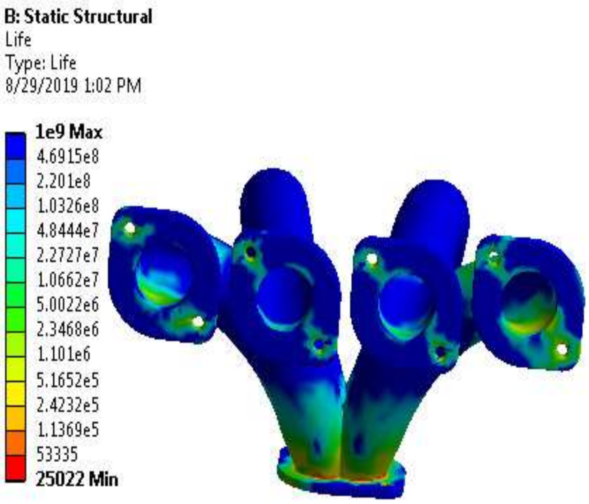

Fig. 7. The number of cycles to failure using SWT equation for coated exhaust manifolds

In Figs. 8 and 9 the number of cycles to failure using Morrow equation is shown for coated and uncoated exhaust manifolds. As it can be seen from Figs. 6 to 9, 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 material26,27]. The area where the maximum temperature and stress is occurred is where the least LCF(confluence area) is predicted. This region is the critical area from the LCF life point of view. The results indicate that the number of cycles of failure for coated exhaust manifold is approximately in the order 2-fold longer, than the results obtained from the uncoated exhaust manifolds. Conclusion is that a TBC has a positive influence on the fatigue life.

As it has been observed in most thermal shock test, the exhaust manifold is broken like Fig. 10. The review of Figs. 2-9 reveals that results of FEA and LCF is corresponded with experimental tests carried out in references, and illustrate the exhaust manifolds cracked in this region.

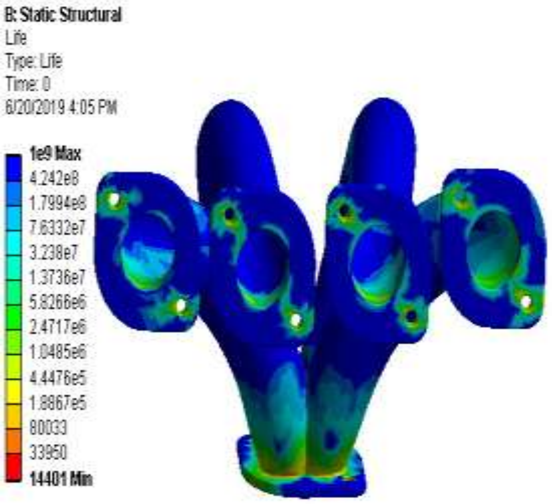

Fig. 8. The number of cycles to failure based on Morrow equation for uncoated exhaust manifolds

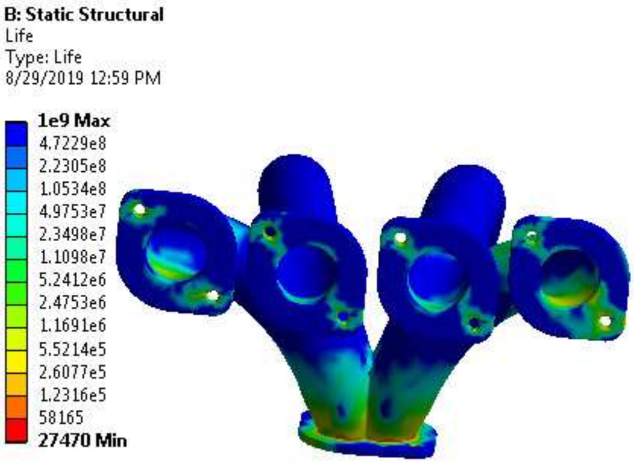

Fig. 9. The number of cycles to failure using on Morrow equation for coated exhaust manifolds

Fig. 10. The cracked exhaust manifold[33]

7- Conclusion

It is shown that exhaust manifolds are subjected to LCF due to the thermal stress resulted from start-stop cycles and must be investigated via FEA[14]. In this study low cycle fatigue life prediction of a coated and uncoated exhaust manifolds is studied by using SWT and Morrow strain life approaches. The results of FEA demonstrated that the temperature distribution in the coated exhaust manifolds dwindles approximately 29°C by virtue of lower thermal conductivity of thermal barrier coating system. Therefore, the exhaust manifolds endures less temperature and fatigue life will increase. The thermo-mechanical analysis proved that Von-Mises stress decreases about 25 MPa by using the TBC system, which can lead to higher fatigue lifetime. LCF life results showed that the number of cycles of failure for coated exhaust manifold is approximately in the order 2-fold longer in comparison to the uncoated exhaust manifolds. 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 FEA instead of experimental tests. Computer aided engineering plays an important role to find the weakness of an exhaust manifold layout at the early stage of the engine development.

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