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Research article

Effect of residual stress in low cycle fatigue for coated exhaust manifold

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Abstract

The exhaust manifolds are subjected to higher loads than before, due to the increasing power output, fuel consumption and exhaust gas emission. Thus, simulation and analysis of fatigue cracks is essential. The effect of residual stress on the thermal stress and low cycle fatigue (LCF) life of exhaust manifolds using strain life methods was investigated. For this purpose, Solidworks software was used to model the exhaust manifolds. Then the thermo-mechanical analysis was carried out to determine the temperature and stress distribution in ANSYS software. Finally, the fatigue life prediction that considers residual stress effect was done. The simulated results proved that the thermal stresses and number of cycles to failure have the most critical values at the confluence region of the exhaust manifolds. The LCF results showed that the number of failure cycles for coated exhaust manifold is about 89% higher than the results obtained from the uncoated exhaust manifolds. Evaluating the residual stress, the TBC improves the number of failure cycles approximately 52% in comparison the uncoated exhaust manifold. The results of FEA proved a very good agreement between numerical simulation results and LCF analysis results, performed in references.

Keywords: Thermo-mechanical fatigue, Finite element analysis, Exhaust manifolds, Residual stress

1- Introduction

The exhaust manifolds are one of the most important automotive parts, which collect combustion 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 is the result of turning the automotive on and off, creates thermo-mechanical fatigue (TMF) loads on the engines exhaust manifolds, making them appear to have the problem of exhaust manifold cracks or fracture. So it is very important to reduce the material temperature in the exhaust manifold in order to improve the fatigue life of the parts [3,4,5,6]. This can be achieved by using a thermal barrier coating (TBC) on the inner surface of exhaust manifold [2,7,8]. TBCs on the piston crown, valves, combustion chamber and exhaust manifold are widely used as coating materials. TBCs used in the automotive industry include two layers, hence top coat (TC) which is mostly made of zirconium oxide due to its low thermal conductivity, high thermal expansion coefficient and a metallic bond coat (BC). The TC and BC layers are made of ZrO2–8wt.%Y2O3 and NiCrAlY, respectively. TBC system allows for higher thermal output, increase engine power, improve combustion and reduce fuel consumption and reduce gas emissions [9,10,11]. TBCs are usually deposited on the inner wall of exhaust manifold by thermal spraying, in which molten ceramic splats hit the surface to be coated with high velocity leading to residual stresses. Residual stress in TBC has four parts: quenching stress, thermal mismatch stress, impact stress, and phase transformation stress. Among these stresses, quenching stress and mismatch stress are the main causes of residual stress. The residual stress can lead to the crack initiation, grown and propagation in the TBCs. The study of the residual stress is becoming a serious problem since the fatigue life prediction of TBCs are often due to the residual stresses [12,13,14].

In the references, previous investigations report several studies related to the thermal stress and TMF in engines exhaust manifolds. The effect of mullite coating on the thermal stress on the exhaust manifold was studied by Padmanabha et al. Around 20% depletion in thermal stresses in shown in the coated circular exhaust manifold around the uncoated circular exhaust manifold [2]. A reduction of about 20% in thermal stresses is indicated in the coated circular exhaust manifold around the uncoated circular exhaust manifold. Saravanan et al. studied the effect of exhaust manifolds with zirconium coating on the efficiency on a gasoline engine. Their study proved that TBC improves engine efficiency and decreases gas emission [1]. 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 longer, than the results obtained from the uncoated exhaust manifolds [8]. Durag Prasad et al. evaluated thermal analysis of coated exhaust manifold. Their research showed that cast iron has the best ability to dissipation heat [15]. Comparing temperature distribution of the coated exhaust manifold proved that the coating with a thickness of 250 μm has better results than other TBCs [16].

Ekström et al. studied several different TBCs for coating an exhaust manifold. The effect of TBC can be improved by increasing the coating thickness [7]. The impact of perimeter fins on LCF life for exhaust manifold was studied by Ashouri. His study 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 [17]. 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 [18]. Failure analysis for an exhaust manifold was performed by Luo et al. Their study showed that the main reason for failure in exhaust manifold is TMF [6].

Salehnejad et al. established a finite element theory to analyze the failure of an exhaust manifold. Their study ruled out the possibility of failure in all spots [19]. 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 [20]. Liu et al. performed a TMF analysis on a ductile cast iron exhaust manifold. Their research showed that the predicted TMF life is close to durability test within factor 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]. Vyas et al. did a coupled CFD-FEA analysis of exhaust manifold for study of thermo-mechanical stress. The obtained results showed that the difference between experimental and simulated results is less than 12% [21]. 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 analysis of exhaust manifold using two different elasto-viscoplastic theories was studied by Mao et al. It is proved that the implemented Chaboche theory in generally more computationally efficient that Sehitoglu theory [22]. In the literature although there are a lot of numerical and experimental evaluations on TBCs in the exhaust manifold, there is a lack of science in the field of studying stress and TMF in coated exhaust manifold considering the residual stress. It is also important to predict the exhaust manifold temperature distribution in order to control the thermal stresses and fatigue life within acceptable level. Therefore, the goal of current study is to predict the stress and fatigue life considering residual stress. For this purpose, Solidworks software was used to model the exhaust manifolds. Then the thermo-mechanical analysis was carried out to get the temperature and stress distribution in ANSYS software. Finally, the fatigue life analysis that considers residual stress effect was performed.

2- Methodology

2-1 The material and its behavioral model

The exhaust manifold material is gray cast iron EN-GJL-250. Due to the thermal spraying process which applies TC and BC layers on the inner wall of exhaust manifold, a thermal analysis is done on the FE model, before TMF analysis [12,13,14]. The temperature of the TC layer is decreased sharply from 2680°C to room temperature during 12000s. This cooling step will cause to the residual stress in the TBC system [12]. Then TMF analysis is performed on the coated exhaust manifold according to quenching stress (σ_q) and the thermal stress (σ_t), as below [13,14]:

$$\sigma_q=\alpha_c E_c \Delta T \quad (1)$$

$$\sigma_t=\frac{E_c}{1-\nu_c}(\alpha_s-\alpha_c)\Delta T \quad (2)$$

Where α_c is the thermal expansion coefficient of coating, E_c is the elastic modulus of coating, ν_c is the poison's ratio of coating, α_s is the thermal expansion coefficient of the substrate and ΔT is the temperature difference. Therefore, the total residual stress is defined by relation:

$$\sigma=\sigma_q+\sigma_t \quad (3)$$

The kinematic hardening parameter (X), describes the translation of the yield surface in the stress space where the isotropic hardening explains the expansion/contraction. The Armstrong–Frederick law has been used to indicate the nonlinear stress–strain equation as below [24]:

$$\dot{X}=\frac{2}{3}C\dot{\varepsilon}_p-\gamma X_{\dot{p}} \quad (4)$$

Where C and γ are material constants. The term $\gamma X_{\dot{p}}$, called the dynamic recovery, causes the nonlinear response of the stress–strain behavior. Integration of Equation (4) with considering the plastic strain, leads to the relationship [5]:

$$X=\upsilon\frac{C}{\gamma}+(X_0-\upsilon\frac{C}{\gamma})+\exp(-\upsilon\gamma(\varepsilon_p-\varepsilon_{p0})) \quad (5)$$

where $\upsilon=\pm1$ gives the flow direction. Then, X_0 and ε_{p0} are the values of X and ε_p at the beginning of the saturated cycle [24].

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 [25, 26]. Heat transfer by conduction per unit area per unit time, in steady situation is described by Fourier equation [25]:

$$\dot{q}=-k\nabla T \quad (6)$$

Where k is the thermal conductivity and ∇T is temperature difference. Heat flux is defined by the following expression [28]:

$$\dot{q}=h_{air}(T_{wout}-T_{air}) \quad (7)$$

$$\dot{q}=h_{gas}(T_{wint}-T_{gas}) \quad (8)$$

where h_{air} is the air heat convection coefficient, T_{out} is the manifold outer surface temperature, T_{air} is the ambient temperature, $h_{gas}$is the gas heat convection coefficient, T_{win} is the manifold outer surface temperature and T_{gas} is the exhaust gas temperature. The standard Stefan–Boltzmann law expresses heat loss due to thermal radiation between the inner wall of manifold and ambient [26]:

$$\dot{q}=\varepsilon\sigma(T_g^4-T_a^4) \quad (9)$$

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.

2-2 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 [5,6,25].

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 [29,30]:

$$E\varepsilon_a\sigma_{n,max}=(\sigma_f')^2*(2N_f)^b+(E\sigma_f'\varepsilon_f')*(2N_f)^{b+c} \quad (10)$$

where σ_f' is the fatigue strength coefficient, E is the modulus of elasticity, $2N_f$ is the number of reversals to failure, b is the fatigue strength exponent, ε_f' is the fatigue strength coefficient and c is the fatigue ductility exponent. 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 [29, 30]:

$$\Delta\varepsilon = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{\sigma_f' - \sigma_{mean}}{E}(2N_f)^b + \varepsilon_f'(2N_f)^c \quad (11)$$

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

2-3 The finite element model and material properties

FEA provides accurate and reliable assessment of temperature and fatigue life results in the engines exhaust manifolds. Finite element analysis allows engineers to identify structural weakness at the early step or to find the root reason of exhaust manifold failures [8,18,27]. The exhaust manifolds studied in this paper are exhibited in Fig. 1.

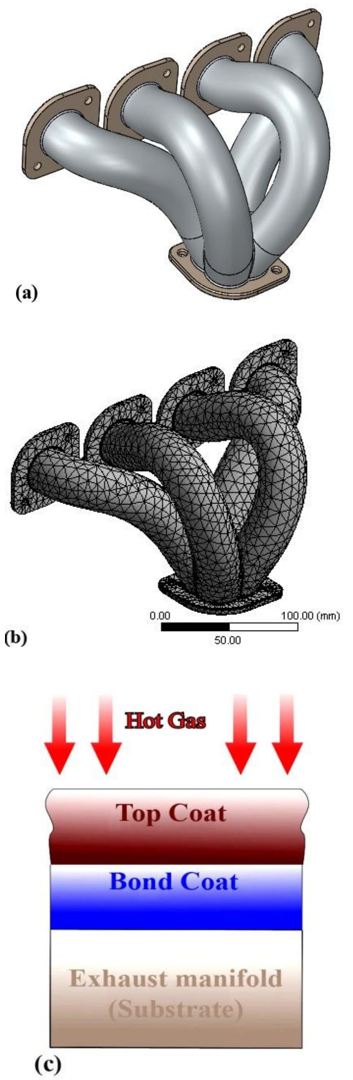

Fig. 1 (a) The exhaust manifold generated by SolidWorks, (b) Finite element model of the exhaust manifold, (c) TBC system

The manifold is gray 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, and Poisson's ratio of 0.26 [8, 18]. 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 [20]. The TC and BC layers are made of ZrO_2–8.%Y2O3 and NiCrAlY, respectively [8].Thermo-mechanical properties of the coating layers are listed in Table 1. The thickness of TC and BC layers are assumed as 135µm and 380µm, respectively [8]. The total number of nodes is 23457 [8,18].

Table 1: Thermo-mechanical properties of Top coat and Bond coat [12, 31]

Characteristics	Bond Coat	Top Coat
Young modules,(GPa)	183 at 25°C 152 at 400°C	17.5 at 25°C 12.4 at 1000°C
Thermal expansion,×10^{-6} (1/ °C)	12.5 at 400°C 14.3 at 800°C 16 at 1000°C	9.68 at 25°C 9.88 at 800°C -
Poisson's ratio	0.3	0.2
Conductivity, (W/m°K)	10.8 at 25°C 32 at 1000°C	0.9 at 25°C 0.3 at 1000°C
Specific heat, (J/kg°K)	450 at 25°C 980 at 1000°C	505 at 25°C 630 at 1000°C
Density,(kg/m^3)	7380 at 25°C 7030 at1000°C	3610 at 25°C 3510 a 1000°C

3- Results and Discussion

3-1 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 control 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 identifies critical locations but also determines the limitation of number of cycles to failure [4,5,6,8,20,27]. 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 [8,20]. Contour results of the temperature distribution are given in Fig. 2. As expected, the temperature maximum is occurred in the confluence region. This corresponds to the results by [8,17,18,20,27].

The main purpose of using a TBC system is reducing the material temperature of the exhaust manifold [2,7,8]. Then, a thermal analysis is performed to determine the temperature field in the coated exhaust manifolds. Contour plots for the coated exhaust manifolds are exhibited in Fig. 3. The maximum value of temperature in the coated and uncoated exhaust manifold is found to be 764.47°C and 704.17°C, respectively. The review of Figs. 2 and 3 shows that although the coated exhaust manifolds temperature is about 60°C higher than the uncoated exhaust manifold, TBC system decreases temperature of the substrate of coated exhaust manifolds about 29°C. That means protecting the substrate of coated exhaust manifolds against high temperatures. Namely, applying the TBCs, decrease heat transfer to the substrate keeping it at lower temperature. Therefore, fatigue life of the exhaust manifold will improve [2,7,20].

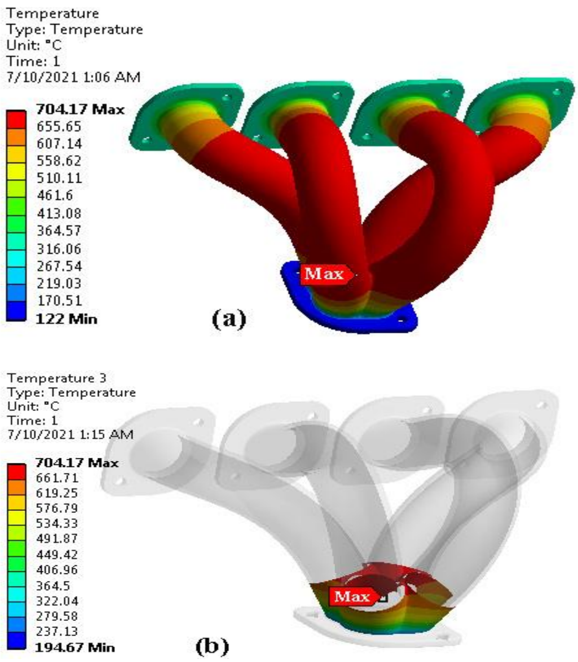

Fig. 2 The temperature distribution in the uncoated exhaust manifold: (a) whole exhaust manifold and (b) confluence area

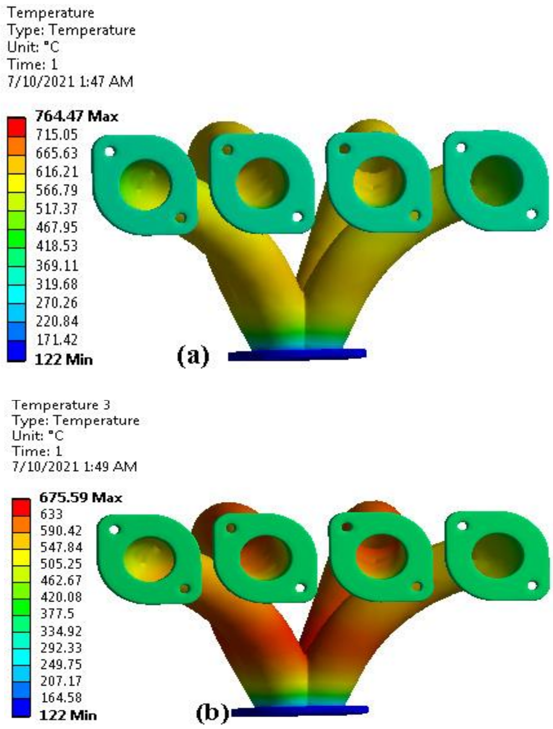

Fig. 3 The temperature distribution in the coated exhaust manifold: (a) without TBC and (b) with TBC

3-2 Mechanical analysis

The exhaust manifolds withstand the mechanical stress and tolerate the thermal stress because of the temperature fluctuations. Thus, the analysis of thermo-mechanical coupling stress on the exhaust manifolds is needed. Stresses and strains created by thermal distribution and mechanical loads are determined by mechanical analysis [5,8,27].

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 [8,17,18]. The structural boundary conditions used to finite element model are given in Fig. 4. Fig. 5 shows the Von-Mises stress field at end of second step.

Fig. 4 Structural boundary conditions

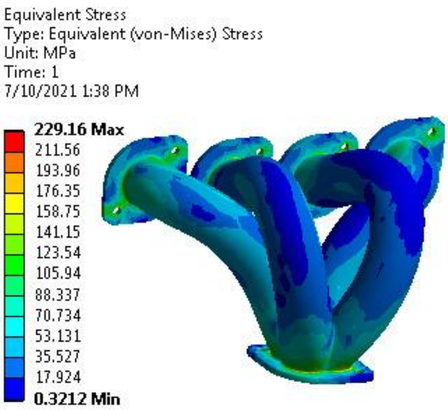

Fig. 5 The Von-Mises stress distribution in the uncoated exhaust manifold

Evaluation of residual stress in the LCF life for coated exhaust manifolds is the main focus of this paper. Residual stress plays a key role in the fatigue life of coated components [13,14]. Von-Mises stress distributions are exhibited in Figs. 6 and 7 for thermal spray process and for thermal spray process plus thermo-mechanical loading, respectively. Fig. 6 shows that the result of residual stress is significant. Thus, residual stress must be considered in the thermo-mechanical analysis of the coated exhaust manifold. Fig. 7 illustrates that TBC system declines the stress distribution in the confluence area. The stress reduction value in the coated exhaust manifold is about 14 MPa which can lead to higher fatigue life in comparison with uncoated exhaust manifold.

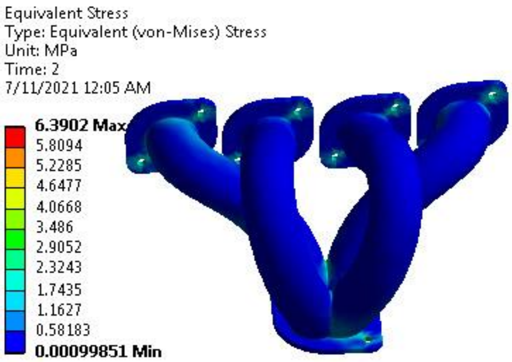

Fig. 6 The Von-Mises stress distribution in the coated exhaust manifold under thermal spray process (residual stress)

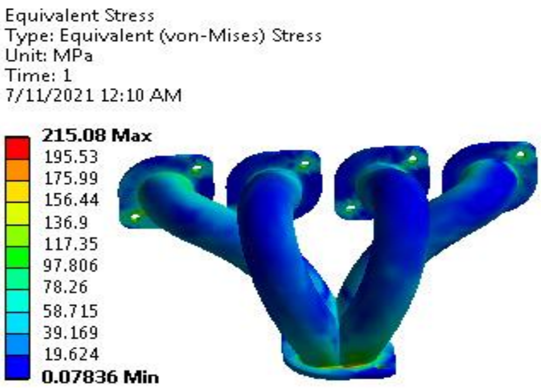

Fig. 7 The Von-Mises stress distribution in the coated exhaust manifold under thermal spray process (residual stress) plus thermo-mechanical loading

The equivalent plastic strain distribution in the exhaust manifold is given in Fig. 8, which is calculated 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 [20,27]. The study of mechanical analysis results, it can be seen that both the stress and plastic strain, which have the dominant effect on the fatigue life are maximum in the confluence region.

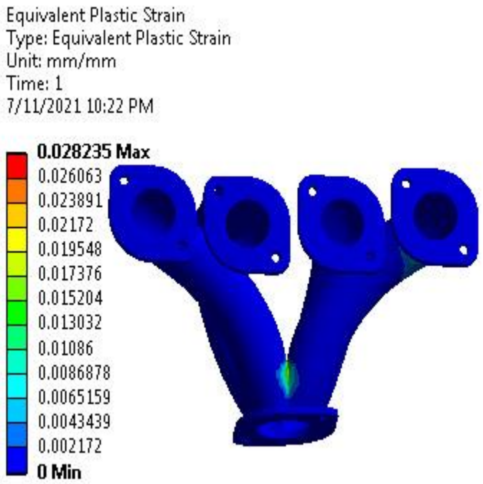

Fig. 8 The equivalent plastic strain distribution

3-3 Low cycle Life prediction

The exhaust manifold bears temperature fluctuations, which introduces thermal expansion and contraction. Due to the constraints used to it, mechanical strain is created. Cyclic changes and accumulated mechanical strain lead to TMF failure of the exhaust manifold. Thus, TMF is very important issue. If a part is not properly designed, crack could occurred at very early stage [5,6,20]. The fatigue life prediction has been done based on LCF method, by applying the Morrow and SWT approaches. Figs. 9 to 11 indicate the number of cycles to failure according to SWT equation for uncoated and coated exhaust manifolds, also considering the result of the residual stress. In Figs. 12 to 14, the number of cycles to failure applying Morrow criterion is represented for uncoated and coated exhaust manifolds.

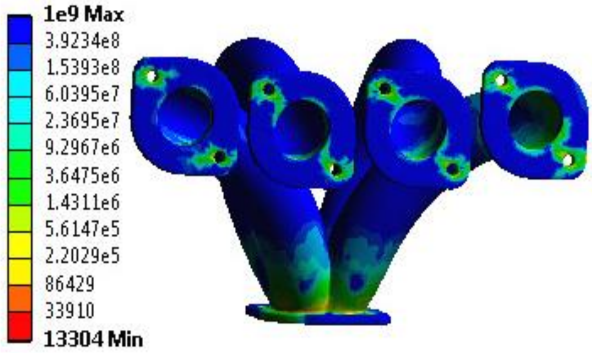

Fig. 9 The number of cycles to failure based on SWT equation for uncoated exhaust manifold

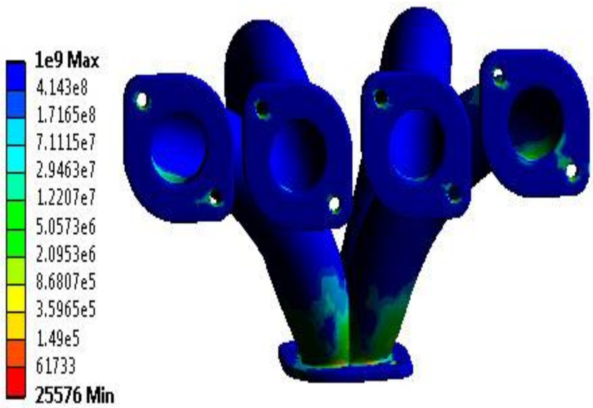

Fig. 10 The number of cycles to failure using SWT equation for coated exhaust manifold without residual stress

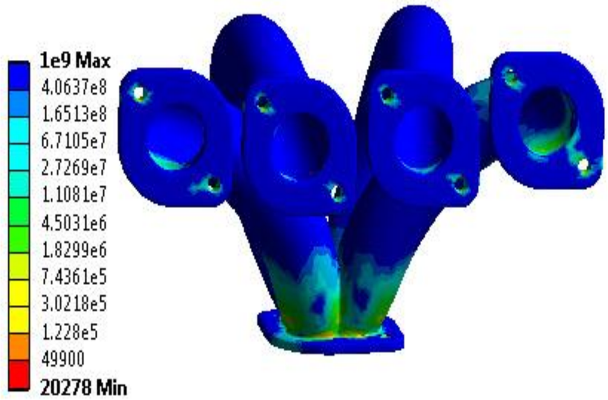

Fig. 11 The number of cycles to failure using SWT equation for coated exhaust manifold with residual stress

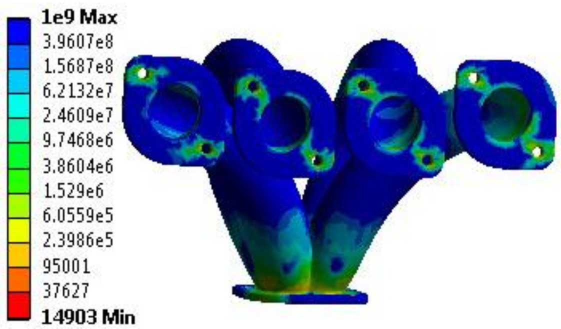

Fig. 12 The number of cycles to failure based on Morrow equation for uncoated exhaust manifold

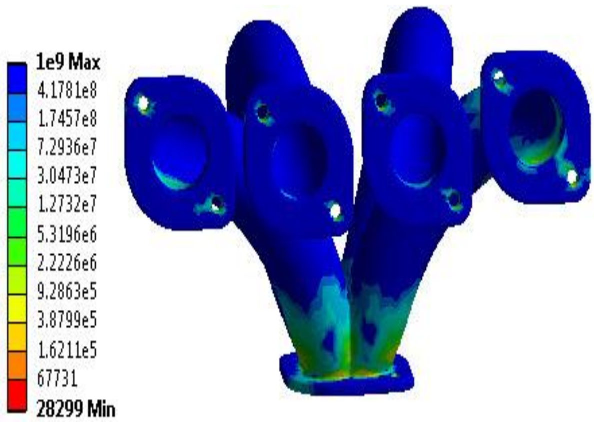

Fig. 13 The number of cycles to failure based on Morrow equation for coated exhaust manifold without residual stress

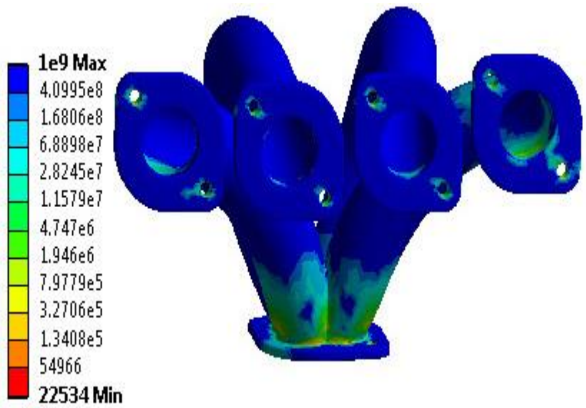

Fig. 14 The number of cycles to failure using on Morrow equation for coated exhaust manifold with residual stress

The review of Figs. 9 to 14, reveals that the number of cycles to failure in the serious region is under 10^4 or 10^5 which imposes LCF life for the exhaust manifold [29,30]. The result of residual tress in LCF for coated exhaust manifold is considerable. Therefore, residual stress must be considered in the TMF analysis of the coated exhaust manifold. The LCF results indicate that the number of cycles of failure for coated exhaust manifold is about 89% higher than the results obtained from the uncoated exhaust manifolds. Evaluating the residual stress, the TBC improves the number of failure cycles approximately 52% in comparison to the uncoated exhaust manifold.

3-4 verification of FEA

As it has been seen in experimental test, the exhaust manifold is broken like Fig. 15. The review of Figs. 2-14 show that results of FEA and LCF is correspond with experimental tests performed in literature, and reported the exhaust manifolds failed in this area.

Fig. 15 The cracked exhaust manifold [33]

The numerical results for the uncoated and coated exhaust manifold are compared in Table 2 with results of previous research. As it can be seen from Table 2, there is a very good agreement between FEA results and reference [8].

4- Conclusion

The exhaust manifold bear LCF due to the thermal stress fluctuations created from start-stop cycles and must be studied via FEA [5, 7]. The goal of this article to evaluate the effect of the residual stress on the LCF life of an exhaust manifold applying Morrow and SWT strain life methods.

Table 2: Comparison of the FEA results and Ref. [8]

Characteristics	FEA	Ref. [8]
Temperature maximum,(°C)	704.17	708.65
Stress maximum,(MPa)	229.16	232.25
LCF using SWT equation for uncoated exhaust manifold,(cycle)	13304	12848
LCF using SWT equation for coated exhaust manifold,(cycle)	25576	25022
LCF based on Morrow equation for uncoated exhaust manifold,(cycle)	14903	14401
LCF based on Morrow equation for coated exhaust manifold,(cycle)	28299	27470

The results of the thermo-mechanical analysis showed that the maximum temperature and stress observed in the confluence area. The LCF results indicated that the number of cycles of failure for coated exhaust manifold is about 89% higher than the results simulated from the uncoated exhaust manifolds. Evaluating the residual stress, the TBC improves the number of cycles of failure approximately 52% in comparison to the uncoated exhaust manifold. The result of residual stress in LCF for coated exhaust manifold was considerable. Thus, residual stress must be investigated in the thermo-mechanical analysis of the coated exhaust manifold. The results of FEA proved a very good agreement between numerical simulation results and LCF analysis results, performed in references. The results of the finite element analysis was corresponded with the experimental tests, performed in references, and indicated the exhaust manifold failed in this area.

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