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Effect of perimeter fins in low cycle fatigue for exhaust manifold

H. Ashouri

Department of Mechanical Engineering, Yadegar-e-Imam Khomeini (RAH) Shahre-Rey Branch, Islamic Azad University, Tehran, Iran, ashouri1394@gmail.com

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ABSTRACT

The effect of perimeter fins on the thermal stress and low cycle fatigue life (LCF) of exhaust manifolds was investigated. For doing this, Solidworks software was used to model the exhaust manifolds. Three Perimeter fins with 4 mm thickness were attached to the modified exhaust manifolds outlet section. Then ANSYS Workbench software was used to determine stress and fatigue life based on Morrow and Smith-Watson-Topper (SWT) approaches. Finally, the improvement of the low cycle fatigue life was studied. The temperature-dependent of material parameters was considered to increase the accuracy of LCF life results. The results of finite element analysis (FEA) uncovered the fact that perimeter fins reduce the temperature distribution in the exhaust manifolds about 32.54°C. 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 modified exhaust manifolds decreased approximately 22MPa for the sake of depletion of temperature gradient, which can lead to higher fatigue lifetime. The results of LCF showed that the number of cycles of failure for modified exhaust manifold is approximately 55% higher than the results obtained from the exhaust manifolds.

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 [1-3]. The exhaust manifold plays important role in engine performance. Particularly, the efficiencies of emission and fuel consumption are closely related to the exhaust manifold. Therefore, it is very imperative to design and develop an exhaust manifold with reliable durability to meet these requirements. Because of the contradictions of the downsizing and the serious thermal-load of modern engine, thermal fatigue failure of the engine components easily happens due to excessive temperature gradient and thermal stress. Exhaust systems are subjected to severe thermal cycles between ambient temperature and approximately 850°C. In conjunction with mechanical constraints, these cycles cause complex stress histories, which may cause failure by thermo-mechanical fatigue (TMF). Modern exhaust system must withstand severe cyclic mechanical and thermal loads throughout the whole life cycle [2, 3].

The fins are extended surface 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 economical solution to heat transfer problems. Fins are widely used in many industrial applications such as air conditioning, refrigeration, automobile, chemical processing equipment, and electrical chips [4].

Numerous papers have been presented on the analysis of stress and fatigue in exhaust manifolds. Evaluation of thermal barrier coating in low cycle fatigue life for exhaust manifold was conducted by Ashouri. The results of low cycle fatigue 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 [5].

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 [6].

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 [7].

Castro Güiza et al. did thermal fatigue fracture of exhaust manifolds. Their analysis indicated that some regions of the cylinder heads entered into the yield region. Hence, fatigue cracks appear in them [8].

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 [9].

Partoaa et al. investigated the effect of fin attachment on thermal stress reduction of exhaust manifolds. Their researches proved that the combined modifications, i.e. the thickness increase and the fins attachments, decrease the thermal stresses by up to 28% and the contribution of the fin attachment in this reduction was much higher compared to the shell thickness increase [10].

Ahmad et al carried out a Thermo-structure simulation of the tractor exhaust manifold. Their analysis showed that stresses which are produced during the operations for 321-Austenitic Stainless steel exhaust manifold, are in the safe region. TMF was the main reason for exhaust manifolds failure [11].

Lujan et al. evaluated the some correlations proposed by other studies for four-stroke engines and presented a new heat transfer model for exhaust systems in two-stroke, high performance, gasoline engines. Comparisons of their proposed model with other models showed negligible differences in the scavenge process-related parameters [12].

In another attempt, Li et al examined Low/high cycle fatigue and thermo-mechanical fatigue of exhaust manifolds. A good correlation between experimental and simulated results was shown [13]. El-Sharkawy et al. investigated transient thermal analysis of exhaust manifolds. According to their study, the experimental and simulated results of temperature match [14].

The analysis of crack mechanism and estimate of lifetime by the vibration measurement of stainless exhaust manifold in firing condition was performed by Sangkim and Joonpark. Their research proved that the vibration level in a vehicle is different from the level in bench condition. By checking resonance frequency and vibration level, we could predict endurance

lifetime [15].
Joshi et al. studied failure analysis and robust optimization of an exhaust manifold diffuser plate. Metallurgical failure analysis coupled with thermal fatigue analysis of the component concluded that thermal fatigue is the root cause of the failure [16].
Optimization of exhaust system hangers for reduction of vehicle cabin vibrations analyzed by Shojaeifard et al. Simulated results indicated that optimization of the locations has resulted in a significant decrease in hanger loads, significantly reducing the vibrations transmitted to the vehicle cabin and increasing the life of the rubber hangers [17].
Evaluation of temperature effect on modal analysis for exhaust manifold was performed by Ashouri. The obtained FEA results showed that gas pressure is effective on the modal analysis and must be considered in the modal analysis of exhaust manifold [18].
According to the reviewed literature, different characteristics of exhaust manifolds such as geometry, shape, materials, and areas of inlet and outlet sections affect the manifold thermal stress. Modifications like increasing the thickness of the manifold solid body and improvement of heat transfer significantly decreases the manifold thermal stresses. The increased thickness solely could not harness the thermal stresses, as there is a limitation for increasing the wall thickness [10].
Thus, This article aims to evaluate the effect of fin attachment on the low cycle fatigue life improvement of an exhaust manifold to reduce the crack creation due to thermal stresses in the exhaust manifold body. For doing this, the first Solidworks software was used to model the exhaust. Then ANSYS Workbench software was used to determine stress and fatigue life based on Morrow and SWT approaches. Finally, the improvement of the low cycle fatigue life was investigated.

2) Methodology

2.1) The material behavioral model

The material employed for the exhaust manifold is the gray cast iron EN-JGL-250. Temperature-dependent stress-strain curves have been taken from experimental results of [24].
In particular, the Chaboche stress-strain relationship has been used to fit stress-strain curves, based on the non-linear kinematic hardening. As kinematic type of hardening is a nearly general occurrence, at least in the range of moderate strains, the corresponding models will have to be used when we want to correctly express either non-proportional monotonic loadings (variation of the loading direction, thermo-mechanical loadings, etc.) or cyclic loadings.
The kinematic hardening variable (X), defines the translation of the yield surface in the stress space where the isotropic hardening defines the expansion/contraction. The Armstrong–Frederick model has been used to represent the nonlinear stress-strain relationship as follows [19]:

$$\dot{X} = \frac{2}{3} C \dot{\varepsilon}_p - \gamma X_{\dot{p}} \quad (1)$$

where $\gamma X_{\dot{p}}$, called the dynamic recovery causes the nonlinear response of the stress-strain behavior. Integration of Equation (1) concerning the plastic strain, for the uniaxial loading, leads to the equation [19]:

$$X = \nu \frac{C}{\gamma} + \left(X_0 - \nu \frac{C}{\gamma} \right) + e^{-\nu\gamma(\varepsilon_p - \varepsilon_{p_0})} \quad (2)$$

where $\nu = \pm 1$ gives the flow direction. Then, X_0 and ε_{p_0} are the values of X and ε_p at the beginning of the saturated cycle [19].
Accuracy of the thermal boundary is the key to temperature analysis, including forced convection heat transfer between high-temperature gas and hot end inner surface, free convection heat transfer and radiation between ambient air and the outer surface, and heat conduct between adjacent parts [13, 20, 21].
The law of heat conduction, also known as Fourier's law, states that the time rate of heat transfer through a material is proportional to the negative gradient in the temperature and to the area at right angles of that gradient through which the heat flows. Mathematically, it can be written as [20]:

$$\dot{q} = -k \frac{dT}{dx} \quad (3)$$

Besides gas convection acting on the interior side of the exhaust manifold, also exterior convection and radiation are decisive in the temperature field. Both free or natural convection and forced convection contribute to the convective heat flux in the exhaust system of an engine.
In all of the above studies, the contributions of free convection to the total external heat transfer

were neglected and the convective component was described solely by a forced convection heat transfer correlation [2, 13, 21]. Heat flux is given by the expression [21]:

$$\dot{q} = h_{\mathrm{air}}\left(T_{\mathrm{w_{out}}} - T_{\mathrm{air}}\right) \quad (4)$$

$$\dot{q} = h_{\mathrm{gas}}\left(T_{\mathrm{w_{int}}} - T_{\mathrm{gas}}\right) \quad (5)$$

The standard Stefan–Boltzmann relation models heat loss due to thermal radiation between the manifold inner surface and environment [20]:

$$\dot{q} = \varepsilon\sigma\left(T_{\mathrm{win}}^4 - T_{\mathrm{air}}^4\right) \quad (6)$$

2.2) Models for TMF life prediction

Thermo-mechanical fatigue is the combined fatigue damage that occurs in a component due to exposure to cyclic mechanical strains and thermal cycles simultaneously. Material properties, mechanical strain range, strain rate, temperature, and the phasing between temperature and mechanical strain all play a role in the type of damage formed in the material.

These types of loadings are most frequently found in start-up and shutdown cycles of high-temperature components and equipment.

Due to today's demands to reduce cost and product time to market, engineering procedures are increasingly using more sophisticated simulation techniques, instead of validation testing.

To ensure field reliability targets, avoid over design and limit the number of required test runs to shorten product development times, early computer-aided engineering (CAE) TMF assessments have to give reliable results.

One of the most challenging simulations is the thermo-mechanical fatigue prediction of exhaust manifolds. Thermo-mechanical fatigue leading to cracks and possible failure in exhaust manifolds is often the limiting factor in the conception of new designs.

The stresses resulting from the thermal cycles often exceed the yield stress at critical locations, which leads to the formation of cracks after a relatively small number of cycles (LCF) [2, 3].

For some materials such as gray cast iron, crack nucleation and/or crack growth is along with 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 the maximum principal strain amplitude plane, $\sigma_{n,max}$. The equation is given by [24-25]:

$$\sigma_{\mathrm{n,max}} = \frac{\sigma_f^2\left(2N_f\right)^b}{E\varepsilon_{\mathrm{a}}} + \frac{\sigma_f\varepsilon_f}{\varepsilon_{\mathrm{a}}}\left(2N_f\right)^{b+c} \quad (7)$$

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

$$\Delta\varepsilon = \frac{\Delta\varepsilon_e + \Delta\varepsilon_p}{2} = \frac{\sigma_f - \sigma_{\mathrm{mean}}}{E}\left(2N_f\right)^b + \varepsilon_f\left(2N_f\right)^c \quad (8)$$

Material constants of EN-JGL-250 gray cast iron are presented in Table1.

Table 1: Material constants of EN-JGL-250 gray cast iron [24]

Characteristics	Values (Dimension)
σ_f'	T=30°C 659.2GPa
	T=500°C 274.7GPa
	T=600°C 163.2GPa
	T=700°C 205.3GPa
ε_f'	T=30°C 0.0533(-)
	T=500°C 0.0318(-)
	T=600°C 0.0149(-)
	T=700°C 0.0434(-)
b	T=30°C - 0.1495(-)
	T=500°C - 0.1022(-)
	T=600°C - 0.0793(-)
	T=700°C -0.1939(-)
c	T=30°C - 0.6428(-)
	T=500°C - 0.5258(-)
	T=600°C - 0.3983(-)
	T=700°C -0.5087(-)

2.3) Finite element model and material properties

The manifold system is subjected to high temperatures and engine pulsations. The thermal damage under alternate heating and cooling cycles result in the appearance of cracks after the accumulation of several hundred cycles.

FEA allows design engineers to identify structural weakness at the early stage or to find the root cause of exhaust manifold failures. In the past, the exhaust manifold is predominantly designed experimentally using costly and expensive component tests.

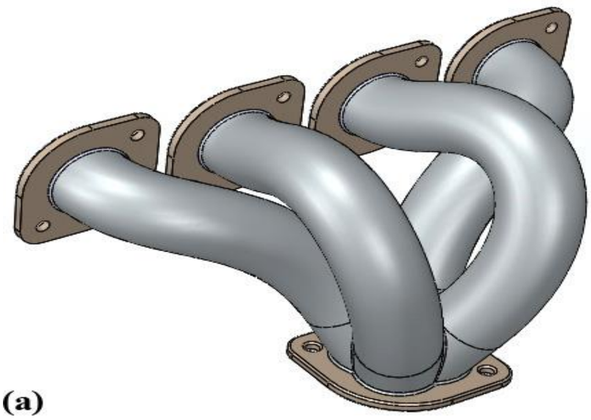
Computer technology and CAE advancement have changed the costly and lengthy traditional development method. With the help of FEA and CAE tools, engineers can perform their analysis and reduce the development cycle in a virtual environment to handle the growing number of model variants [2, 5, 7].

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

The manifold is cast from gray iron with thermal conductivity of 48 W/mm°C, a density of 7200 kg/m^3, 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 thermal conductivity of 167W/mm°C, a density of 2700 kg/m^3, Young's modulus of 68.9 GPa, and a Poisson's ratio of 0.33 [5, 18].

Ten bolts fasten the manifold to the cylinder head. The bolts are made from steel, with 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 [7]. There are several methods to insert the values of C and γ into ANSYS software that one of which is entering yield stress at plastic strain using the tensile test [5].

The yield stress at plastic strain was extracted from the source [24], using the results of conducted experiments on EN-JGL-250 gray cast iron and entered into the ANSYS software. The model has then meshed with tetrahedral solid elements for improving the accuracy and acceptability of the obtained results. The total number of nodes is 53382, whereas solid elements are 23457.



(a)

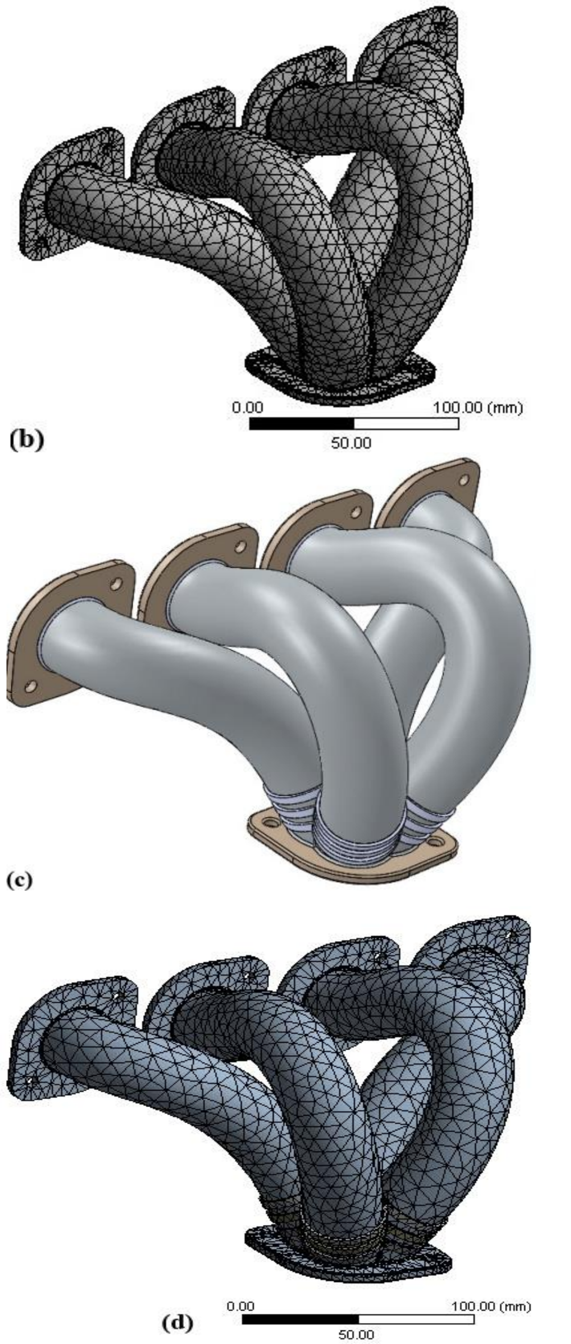


Figure 1: (a) The exhaust manifold generated by SolidWorks, (b) Finite element model of the original exhaust manifold, (c) Modified exhaust manifold with fins attachment, and (d) Finite element model of the modified exhaust manifold

3) Results and Discussion

3.1) Thermal Analysis

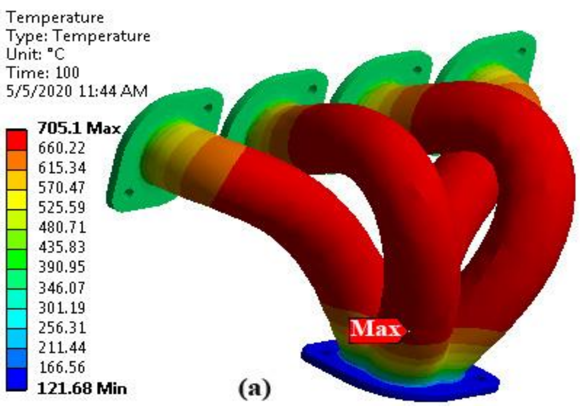
The main variation of thermal load arises from start-stop cycles and involves large temperature changes. From the variation of load in different operation states, the thermal flux changes, and additional minor thermal cycles are generated.

Because of this, the first step in the exhaust manifold development is the accurate metal temperature prediction of the exhaust manifold. A significant influence on the TMF life span is due to the temperature loading. The temperature field not only determines the critical locations but also is decisive in limiting the number of cycles to failure.

The objective of the heat transfer analysis is to determine the three-dimensional temperature distribution in the exhaust system. This is a dominant step in the life assessment process because the accuracy of thermal data governs the accuracy of the mechanical response of the structure; therefore, the estimated fatigue. To accomplish this operation, exhaust manifolds are subjected to a severe thermal cycle that includes a cold start at the beginning of the operation, a full load regime while the engine is running at normal conditions, and a cooling period after the engine has stopped [2, 5, 7, 9].

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 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 [5, 7]. Figure 2 shows the temperature field at the end of heating. It is maximized in the confluence region. This corresponds to the results by [1, 2, 5, 9].



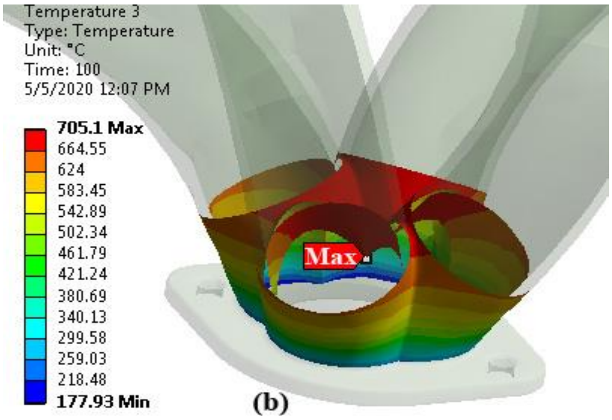
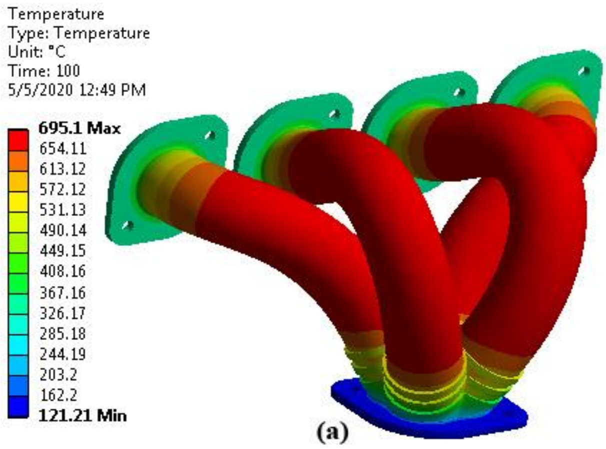


Figure 2: The temperature distribution in the original exhaust manifold: (a) whole exhaust manifold and (b) confluence area

It is known that temperature elevation imposes a significant adverse impact on fatigue [1, 5, 7]. Contour results of the temperature distribution in the modified exhaust manifolds are shown in Figure 3.



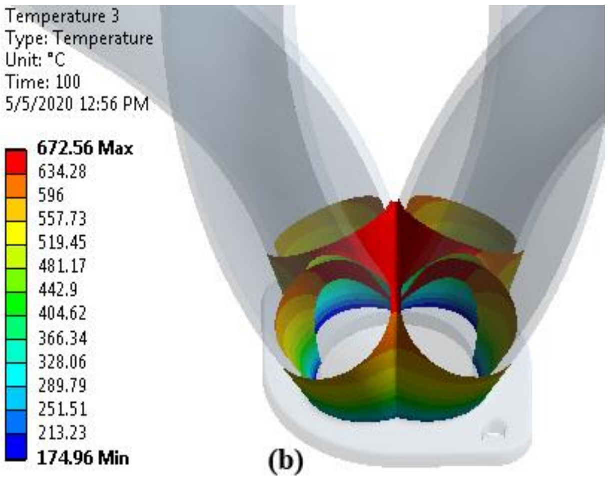


Figure 3: The temperature distribution in the modified exhaust manifold: (a) whole exhaust manifold with fins attachment and (b) confluence area with no fins

Figure 4 shows the calculated temperature as a function of time at a point in the junction region where four manifold tubes coverage. It was indicated that from the engine start, the temperature would be elevating slowly until it was stable and then it was decreasing.
From 450~460S, the trend of the temperature curve was nearly close to a straight line, implying that the exhaust manifold temperature reached a steady state. Starting from 460S to the cycle end, the temperature decreased with a significant tendency. The confluence area is a crucial region [1, 5, 7]. The temperature gradient changes from 705.1°C to 177.93°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 672.56°C to 174.96°C. It means that the maximum temperature of modified exhaust manifolds reduces up to 32.54°C (from 705.1°C to 672.56°C) by using the perimeter fins. This can lead to lower stress values in the modified exhaust manifolds. Thus, the fatigue life can be improved [10].

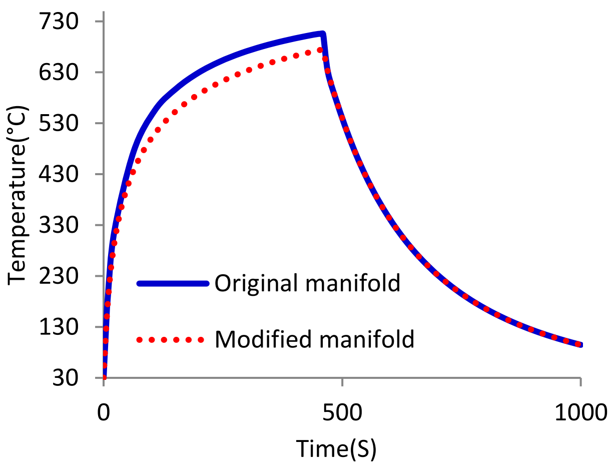


Figure 4: The temperature variant in the hottest spot for a single start-stop cycle

Contour results of the temperature distribution in the exhaust manifolds carried out in references is shown in Figure 5. The review of Figures 2 and 5 reveals a very good agreement between temperature distribution and thermal analysis results, carried out in references.

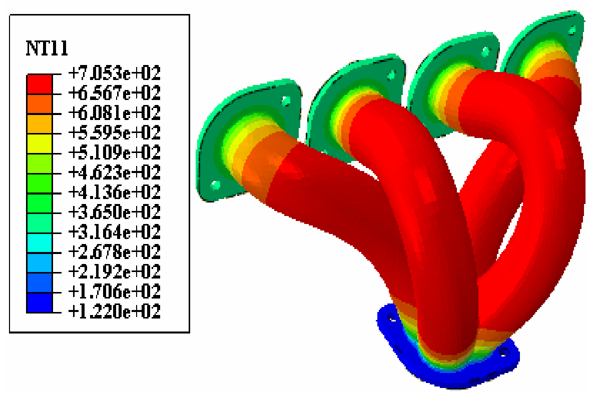


Figure 5: The temperature distribution in exhaust manifold [18]

3.2) Mechanical analysis

The temperature distribution is the most important boundary condition to drive the mechanical analysis. Another important load to consider on the exhaust manifold design is the combination of mechanical load provided by bolt fasten and the thermal load due to temperature gases [5, 9]. According to many authors [1, 5, 6, 9, 22], the mechanical and thermal loads together is the major method that can lead the exhaust manifold to fatigue failure. To perform the elastoplastic thermal stress analysis, it is necessary to consider the temperature distribution, mechanical constraints, and temperature-dependent material properties [1, 5, 9].
Gas pressure and bolt tightening for both exhaust manifold and engine head, and exhaust manifold and catalyst have been taken into account. The nodal temperatures obtained by the thermal analysis have been then imported as initial conditions into the model for the mechanical analysis, to calculate stresses and strains generated by the application of the thermal cycles. As explained in Section 2, the gray cast iron behavior has been modeled using a non-linear hardening model, which parameters are temperature-dependent.
It is assumed that the exhaust manifolds are securely fixed to a stiff and bulky engine cylinder head and catalyst, so the flange surfaces are constrained in the direction normal to the cylinder head and catalyst but are free to move in the two lateral directions to account for thermal expansion. Figure 6 shows the structural boundary conditions applied to the finite element model of an exhaust manifold for structural analysis. Flange surfaces are fixed in their normal directions. Figure 7 shows the equivalent stress distribution in hot conditions.

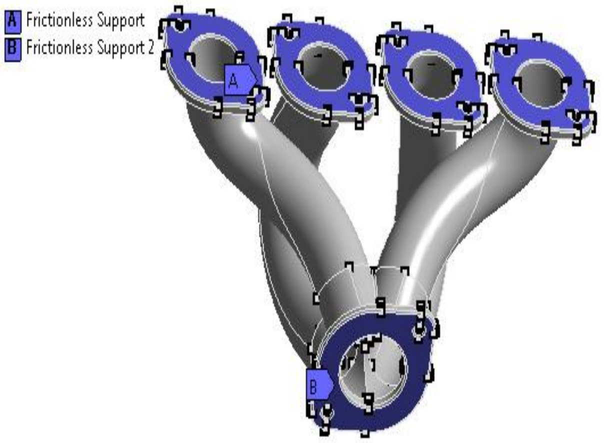


Figure 6: Structural boundary conditions

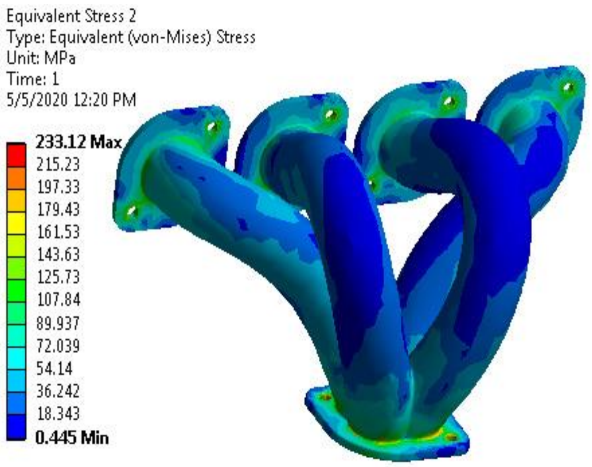


Figure 7: The Von-Mises stress distribution in the original exhaust manifold

Fatigue fractures in manifolds are thought to result from low cycle fatigue of constant strain due to the repetition of thermal stress. In this case, the dominant factor determining whether cracks will occur is the plastic strain range [3, 7]. Equivalent plastic strain distribution is depicted in Figures 8 and 9. It can be seen that both the stress and plastic strain, which have the dominant effect on the damage evolution are maximum at the junctions (critical areas). As stated in sources [3, 7] the initiation of fatigue cracks in exhaust manifolds occurs where plastic strain happens because of thermo-mechanical loads. Stress contour results for the modified exhaust manifolds are presented in Figure 10. Figure 10 demonstrates that the perimeter declines the stress distribution in the confluence area. The stress reduction value in the modified exhaust manifold is about 22 MPa, which can lead to higher fatigue lifetimes in comparison to the original exhaust manifold.

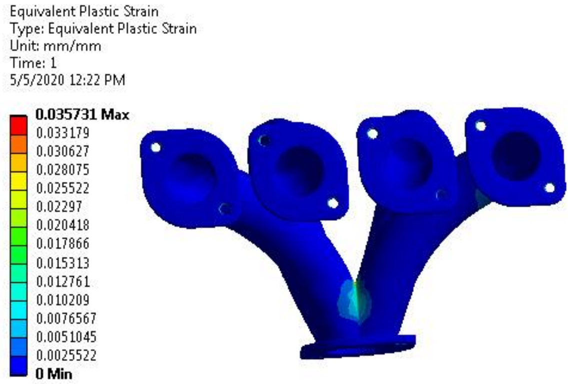


Figure 8: The Equivalent plastic strain distribution in the original exhaust manifold

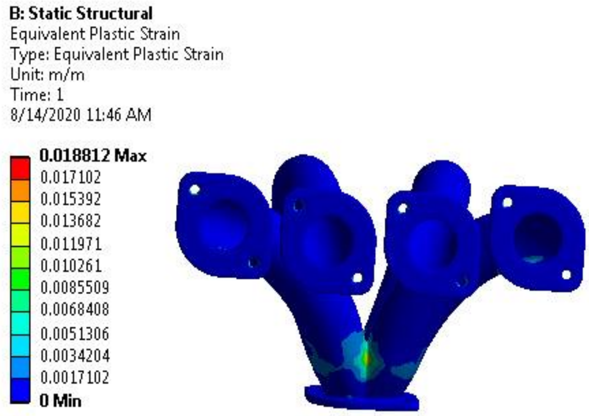


Figure 9: The Equivalent plastic strain distribution in the modified exhaust manifold

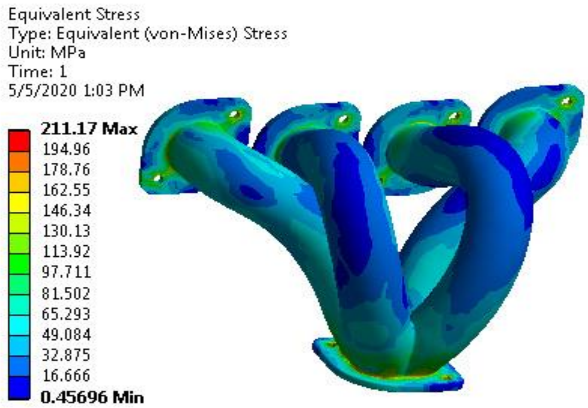


Figure 10: The Von-Mises stress distribution in the modified exhaust manifold

3.3) Low cycle life prediction

High-temperature combustion gas flows past the inner wall of the manifold, so the part is subject to cyclic thermal loads as the engine warms up and cools down as it is started and stopped. This repeated thermal stress causes localized thermal plastic strain to build up in the manifold, and that eventually adversely affects the lifetime of the manifold as thermal fatigue cracks develop [1, 5].

Many lifetime predictions approaches have been published over years. TMF life assessment approaches could be classified as strain-based, energy-based, damage parameters, fracture mechanics, cumulative, and micro-structural approaches. Independent of the theory used, the life prediction is based on functions of the induced strains and stresses due to thermo-mechanical loading and the material parameters [22, 23]. In [25], a good correlation of life span results for gray cast iron was shown using Morrow and SWT approach.

The fatigue damage estimation has been performed according to LCF approach, by using the Morrow and SWT equations, also considering the effects of the mean stress. Figures 11 and 12 represents the number of cycles to failure based on SWT criterion for original and modified exhaust manifolds. In Figures 13 and 14, the number of cycles to failure using Morrow equation is shown for original and modified exhaust manifolds.

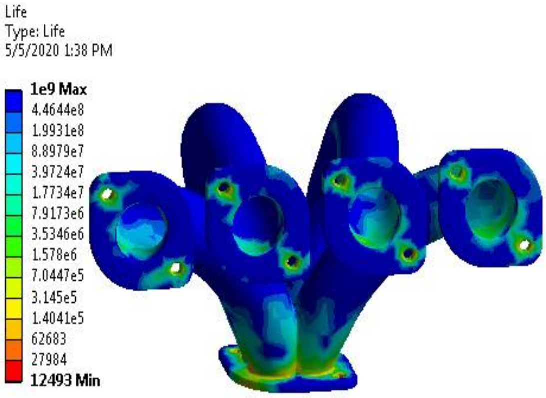


Figure 11: The number of cycles to failure based on SWT equation for original exhaust manifold

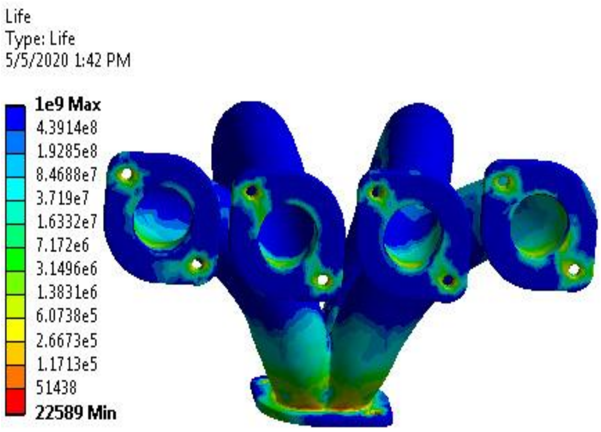


Figure 12: The number of cycles to failure using SWT equation for modified exhaust manifold

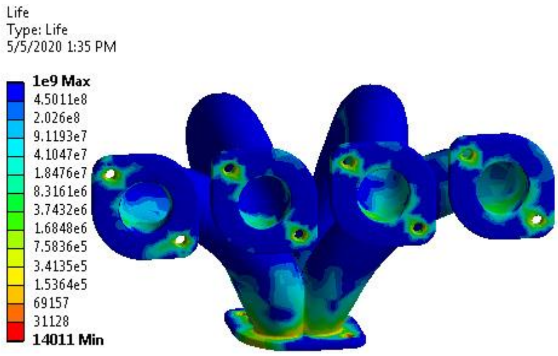


Figure 13: The number of cycles to failure based on Morrow equation for original exhaust manifold

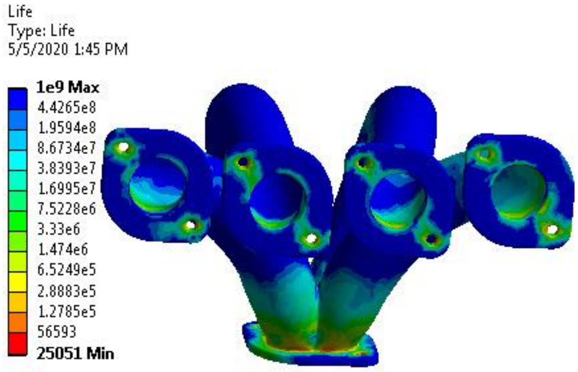


Figure 14: The number of cycles to failure using on Morrow equation for modified exhaust manifold

It is noted that the average stress and the amplitude of stress are 164.46 MPa and 58.98MPa, respectively. The results indicate that the number of cycles of failure for modified exhaust manifold is approximately 55% higher than the results obtained from the original exhaust manifolds. As it has been observed in most thermal shock test, the exhaust manifold is broken like Figure 15. The review of Figs. 2-14 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.

Figure 15: The cracked exhaust manifold [26]

4) 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 [5, 7]. The aim of this work to evaluate the effect of fin attachment on the low cycle fatigue life improvement of an exhaust manifold to reduce the crack creation due to thermal stresses in the exhaust manifold body.

The results of FEA demonstrated that the temperature distribution in the modified exhaust manifolds dwindles approximately 16.33°C. Therefore, the exhaust manifolds endure less temperature and fatigue life will increase. The thermo-mechanical analysis proved that Von-Mises stress decreases about 19 MPa by using the perimeter fins, which can lead to a higher fatigue lifetime.

LCF life results showed that the number of cycles of failure for modified exhaust manifold is approximately 60% higher in comparison to the original exhaust manifolds. The lifetime of this part can be determined through FEA instead of experimental tests.

List of symbols

X	Back stress
C	Material constant
γ	Material constant
$\dot{q}$	Heat flux
k	Thermal conductivity
h_{air}	Air heat convection coefficient
h_{air}	Gas heat convection coefficient
ε	Emissivity
σ	Standard Stefan–Boltzmann constant
T_{air}	Air temperature
T_{gas}	Manifold temperature
σ'_f	Fatigue strength coefficient
$2N_f$	Number de reversals to failure
b	Fatigue strength exponent
ε'_f	Fatigue strength coefficient
c	Fatigue ductility exponent
$\Delta\varepsilon$	Strain amplitude
σ_{mean}	Mean stress

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اثر پره‌های حلقوی بر عمر خستگی کم‌چرخهٔ چندراههٔ دود

حجت عاشوری

دانشکده مهندسی مکانیک، واحد یادگار امام خمینی(ره) شهرری، دانشگاه آزاد اسلامی، تهران، ایران، ashouri1394@gmail.com

چکیده

اثر پره‌های محیطی بر تنش‌های حرارتی و عمر خستگی کم‌چرخه چندراههٔ دود بررسی شده است. ابتدا طرح چندراههٔ دود در نرم‌افزار سالیدورکز شاخته شد. سپس سه پرهٔ محیطی با ضخامت چهار میلیمتر در قسمت خروجی چندراههٔ دود طراحی شد. از نرم‌افزار ANSYS Workbench به منظور تعیین تنش و عمر خستگی براساس معیارهای مارو و اسمیت-واتسون- تاپر استفاده شده است. درنهایت، بهبود عمر خستگی کم‌چرخه ارزیابی شد. با هدف افزایش دقت نتایج عمر خستگی کم‌چرخه، خواص مواد وابسته به دما تعریف شد. نتایج تحلیل اجزای محدود نشان داد که پره‌های محیطی باعث کاهش دمای چندراههٔ دود در حدود ۳۲،۵۴ درجهٔ سانتیگراد می‌شوند. در نتیجه چندراههٔ دود دمای کمتری را تحمل می‌نماید و عمر خستگی آن افزایش خواهد یافت. نتایج تحلیل گرمائی-مکانیکی نشان داد که به علت کاهش دما، تنش در چندراههٔ دود اصلاح شده حدود ۲۲ مگاپاسکال کاهش می‌یابد که باعث افزایش عمر خستگی خواهد شد. نتایج تحلیل عمر خستگی کم‌چرخه نشان داد که تعداد چرخه‌های گسیختگی چندراههٔ دود اصلاح شده حدود ٪۵۵ از چندراههٔ دود اولیه بیشتر است.

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خستگی گرمائی-مکانیکی

تحلیل اجزاء محدود، چندراههٔ دود

پره‌های حلقوی