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Thermomechanical Analysis of Diesel Engine Exhaust Manifold

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Abstract

This study focuses on the Termomechanical Fatigue (TMF) analysis for an exhaust manifold. Bolt tension and temperature field has been applied in order to get variation on stresses, going from room load condition to a full load condition. The temperature field has been acquired from 1D simulation and adjusted to fit experimental values measured on the vehicle. Low cycle fatigue (LCF) has been considered to evaluate the exhaust manifold under the stress cycles produced by temperature fluctuation. Thermal and stress analysis have been performed by Abaqus package. An in-house code has been employed in the fatigue analysis. The bolt torque and the temperature field on the engine and exhaust manifold are the loads considered in the analysis.

Introduction

Since the development of internal combustion engine, the constant requirement for improvement of the power efficiency, cost reduction and environmental emissions are targets that have challenged the engineering community. As a result, in the last decades new design and fabrication technologies have been developed. Among several components in the engine, the exhaust manifold plays important role to achieve the above targets.

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. Actually, in some cases the gases into the exhaust manifold can reach up to 1000°C.

As the temperature arises, the expansion of manifold is restrained by bolts that join it on the cylinder head and on the turbocharger. Such restrains introduce stresses and strains along the manifold body. Besides, as the engine operates from a low temperature state (room temperature) to a high temperature condition (full load engine on), a stress cycle is developed. Such behavior can introduce fatigue failure on critical points of the exhaust manifold and need to be prevented during the design stage.

To prevent fatigue failures, the material selection and the structure evaluation under loads play important role on the design of exhaust manifold. Concerning material properties, the main characteristics required for the manifold material include good thermal fatigue strength and high oxidation resistance. Hence, ferrous alloys are predominantly employed in the manufacturing of exhaust manifold.

In the present days, exhaust manifolds are manufactured mainly with cast iron and stainless steel. By increasing Silicon (Si) and Molybdenum (Mo), the cast alloys increases the heat properties, ductility and strength at high temperatures [1] to [5]. Miazaki et.al.[6] has investigated the addition of Si, Mo and Chromium (Cr) on ferritic stainless steel. They conclude that addition of Mo introduces a notable effect in expanding oxidation resistance and the strength at high temperatures. The authors also noticed that the presence of Si improves the oxidation resistance as well, with minor effects on high temperature strength. Despite the improvements on stainless steel material, the cast iron is still used as exhaust manifold material for cost saving reasons.

Also important in the exhaust manifold design is the consideration of various failure modes in the design stage. In this way, the vibration that comes from engine excitation or road irregularities can suffers dynamic amplification and leads the manifold to failure. For this reason, in the last few years many intensive investigations have been performed to deal with vibration in vehicle exhaust systems [7] to [10]. Zou et. Al [11] shows that the temperature pre-stress has different effect on the exhaust manifold structural modes, and so, the temperature effect on material mechanical properties should be taken into account on exhaust manifold modal analysis. Xu et.al [12] and Yuan [13] implemented numerical tests to evaluate the effects of vibration generated by road and engine on the engine exhaust system.

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. According to many authors [14],[15],[16] the mechanical and thermal loads together is the major method that can lead the exhaust manifold to fatigue failure. While loads from engine vibration or from road irregularities can be treated in a high cycle fatigue (HCF) analysis, the excessive deformation on the exhaust manifold due to thermal loads requires a low fatigue analysis (LCF).

The fatigue on exhaust manifold due to high temperature gases is usually divided in three distinct failure mechanisms: oxidation, damage, creeping damage and mechanical (plasticity) damage.

The oxidation damage process includes crack nucleation and crack propagation on a surface oxide layer. The growing occurs the new oxide layer formed at the tip of the crack is break, exposing the new metallic surface to the environment. Sehitoglu [16] has proposed models for oxidation fatigue. However, the database for oxidation model parameters are obtained by usually time-consuming and expensive tests, so the usually way to reduce the oxidation is during the material selection.

Material creep has been studied by Taira [18], which proposed a model including creeping and oxidation effects. In general, the results had good correlation with experimental tests, but with some irregular results for temperatures around 650°C to 900°C. Sehitoglu [17] fatigue model also consider the effects of material creeping. As in the case of oxidation, the model parameters for creeping also are evaluated by expensive tests and usually rare in literature.

Although there is studies showing creep deformation as the main influence for the total damage [19], other studies [14, 15], [16] shows that plasticity has major contribution on fatigue failures of exhaust manifold.

In this scenario, the present work shows the analysis of GGG50SiMo exhaust manifold for a 6 cylinders engine. As oxidation and creep properties were not available, the analysis considers only the damage caused by cyclic plasticity. To accomplish this aim, in the next section the analysis sequence is established. Then the FE modeling details and results are shown. FE stress and strain results are the inputs to estimation of low-cycle fatigue (LCF) life. For confidential reasons, only qualitative results are shown.

Analysis Procedure

The analysis of exhaust manifold, regarding to thermal and mechanical loads, can be done in a full coupled thermal and mechanical approach, usually named “two way coupled analysis” or in a “one way coupled analysis”. The work herein described was done in the later form. So, thermal variables evaluated in a heat transfer analysis are used as input to the mechanical stress analysis. There is no influence of mechanical analysis back to the original heat transfer analysis (as occurs in the two way coupled solution). From now on, the term “full load” condition will refers to the engine at maximum load, and the “room condition” will be used to engine off. Both thermal and mechanical FE simulations have been performed using Abaqus 2016 package. The procedure can be detailed as follows:

Temperature Field Data

First, the temperature distribution for full load needs to be set. The convection heat transfer coefficients (HTC) for inner and outer walls of exhaust manifold system (manifold, intake and exhaust ports of cylinder) and the temperature distribution on the system was evaluated by a 1D thermal simulation. In Figures 1 to 3 are illustrated the distribution of temperatures and HTCs on the system. As shown in Appendix, additional experimental temperatures, measured on additional locations over the exhaust system, was also used as input to calibrate the temperature field for full load condition.

Heat Transfer Analysis

In the next step, the HTCs and temperatures obtained before have been used as input to a heat transfer analysis. While temperature and HTCs are input in some areas of the model, the output of heat transfer analysis is the temperature distribution over the entire system. After three local adjustments, a temperature distribution that agrees with measured values has been founded.

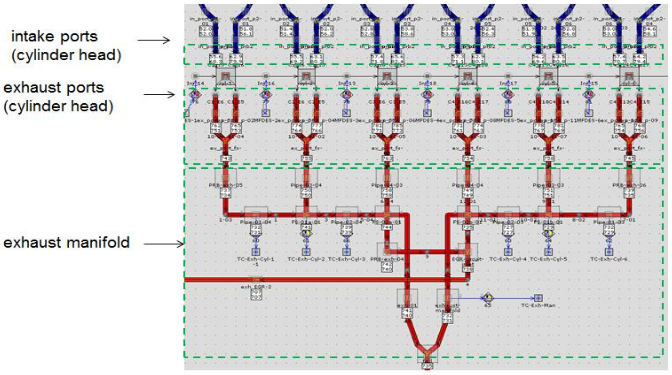

Figure 1.Temperature evaluation: 1D simulation.

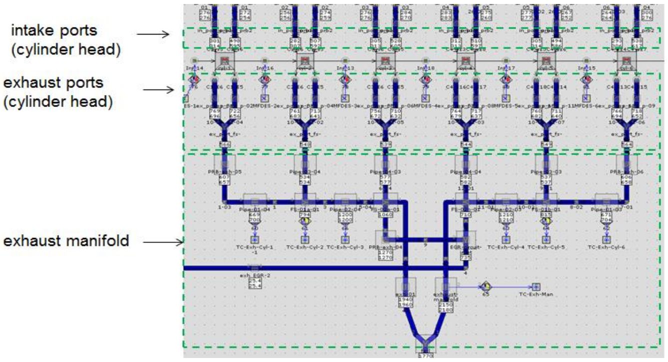

Figure 2.HTC’s distribution: 1D evaluation.

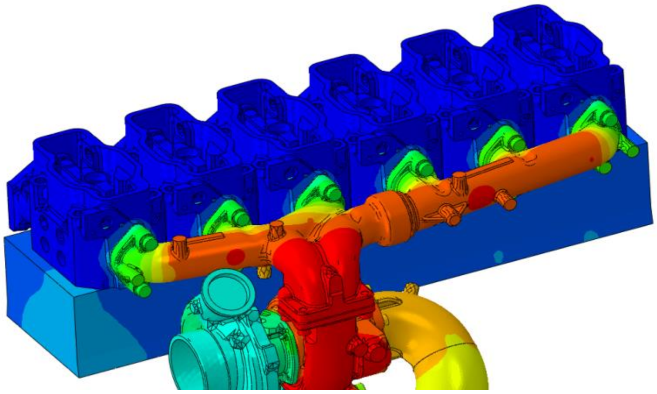

Figure 3. Temperature distribution for full load condition.

Stress-Strain Analysis

The stress analysis is the next step. The temperature distribution obtained in the heat transfer analysis is used as input to the stress evaluation. Before the input of temperature field, it is necessary to join the components (cylinder head to exhaust manifold, exhaust manifold to turbocharger and exhaust manifold to elbow pipe) by fastening the bolts on those interfaces. Figures 4 to 7 illustrate the bolt modelling for each mentioned interface.

Still in the stress analysis, the thermal loads are applied after bolt load. The temperature field corresponding to the full load condition is shown in Figure 3,

After the warming to full load condition, the model is cooling to the room load condition. This process, illustrated in Figure 11, is repeated sufficient times necessary to accommodate cyclic plastic strain on the exhaust manifold. Usually few repetitions are necessary. In this work after four repetitions there was an accommodation of exhaust manifold deformation.

Damage analysis

The fatigue damage estimation has been performed according to LCF approach, by using the Morrow's equation[12], also considering the effects of the mean stress.

Oxidation and creep analysis, as stated before, has not been considered. The cyclic plasticity analysis has been performed according to Morrow's equation[20], including the effects of the mean stress. The equation is given by

$$\varepsilon_a = \frac{\sigma'_f - \sigma_m}{E}\left(2N_f\right)^b + \varepsilon'_f\left(2N_f\right)^c \qquad (1)$$

where

ε_a – total strain amplitude.

ε'_f – fatigue ductility coefficient.

c – fatigue ductility exponent.

σ'_f – fatigue strength coefficient.

σ'_f – fatigue strength coefficient.

σ_m – mean stress.

b – fatigue strength exponent.

$2N_f$ – number de reversals to failure.

For each node in the model, FE results from stress-strain analysis furnish the strain amplitude and mean stress. The cycle is considered from the values (stress and strain) from room load condition to full load condition. The other terms are material coefficients, which are usually known to room temperature. A regression analysis was used to determine those coefficients, considering fatigue properties behavior at high temperatures for ferrous materials, as explained in [21].

The LCF method was implemented by an in–house code, which works directly with Abaqus outputs.

FE Model

The FE model for exhaust manifold analysis includes the manifold itself and also the attached parts: cylinder head, turbocharger, turbine and elbow pipe. A slice of a simplified engine block also has been included on the model, as illustrated in Figure 4.

The bolts, washers, cylinder head and elbow pipe have been modeled as elastic materials. Bolts and washers have been modeled with hexahedral elements (8 nodes). All others components were modeled with 10 nodes tetrahedral elements.

The manifold is divided in two parts, in order to accommodate the axial displacements due to material expansion.

The manifold and turbocharger were modeled as elastic-plastic, temperature-dependent material. Stress-strain curves for several temperatures are shown in Figure 8.

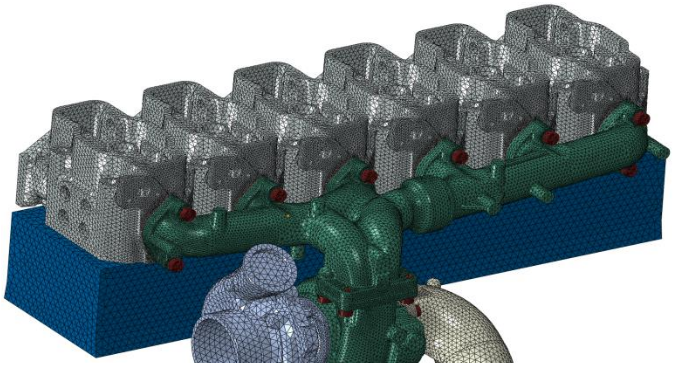

Figure 4.FE Model of exhaust manifold analysis.

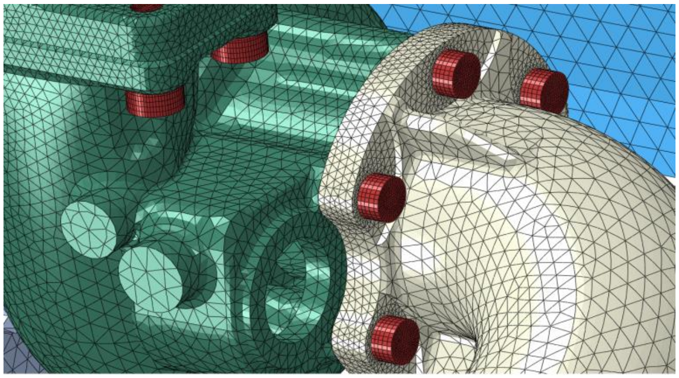

Figure5.Meshing detail of turbocharger / elbow pipe interface.

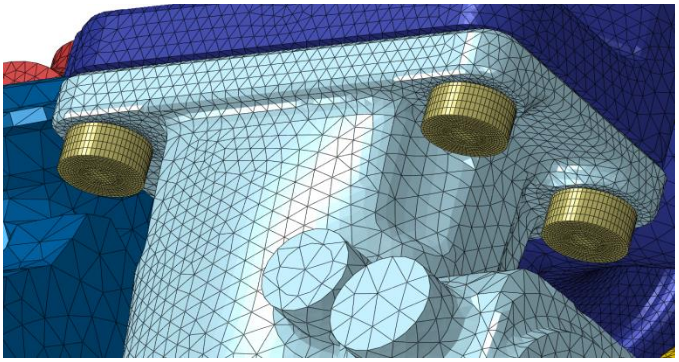

Figure 6.Meshing detail of turbocharger / manifold interface.

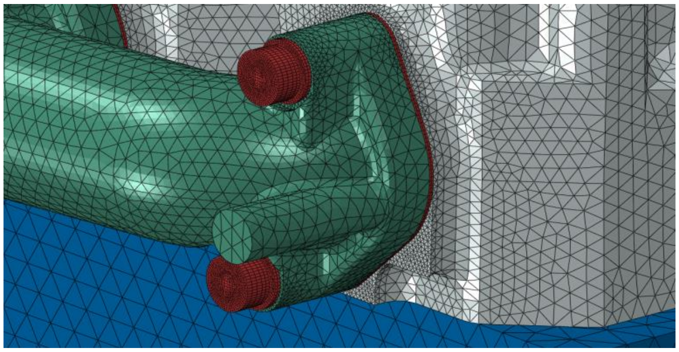

Figure 7.Meshing detail of cylinder head / manifold interface.

Materials

Representative stress-strain curves of GGG55–SiMo cast iron as illustrated in Figure 8. As shown, there is a significantly reduction in the material’s strength with the increasing of temperature.

The material’s elasticity modulus is also variable as a function of temperature. At 800^{o}C, the Young modulus decay to almost 20% of value found at room temperature. The young modulus variation is illustrated in Figure 9.

Materials of cylinder head and elbow pipe working only in elastic range. However, the dependency of elasticity modulus on temperature has been considered for these materials.

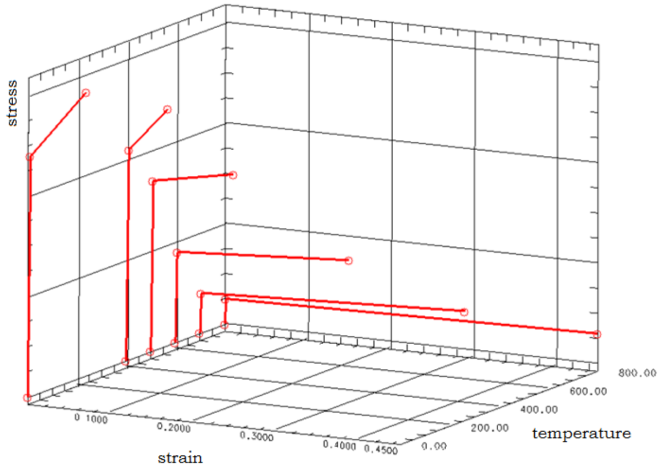

Figure 8. Stress-strain curves as temperature function.

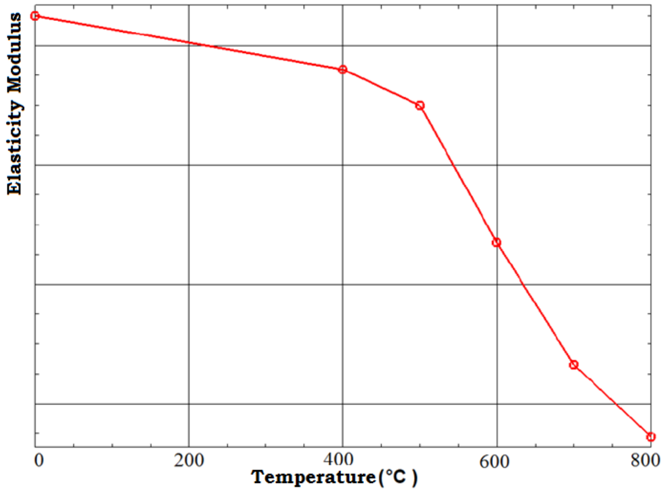

Figure 9.Elasticity modulus vs temperature.

Boundary Conditions

As shown in Figure 10, the cylinder head and a simplified slice of the engine block have been modeled.

Restraints

For stress-strain analysis, the FE model is restrained on the bottom of the simplified engine block slice, as depicted in Figure 10. Also the model was restrained on the elbow pipe bracket.

Contact Interactions

In order to consider the effects of bolt loading, bolted joint sliding during the thermal expansion and bolted joint openings, contact interactions between components have been considered. As illustrated in Figure 10 (not all contacts are shown), the model contains the following contact interactions:

- cylinder head and gasket;
- gasket and manifold;
- exhaust manifold and washer;
- washer and bolt head;
- turbocharger gasket and manifold;
- turbocharger gasket and turbocharger;
- turbocharger and elbow pipe;
- between two manifold parts;

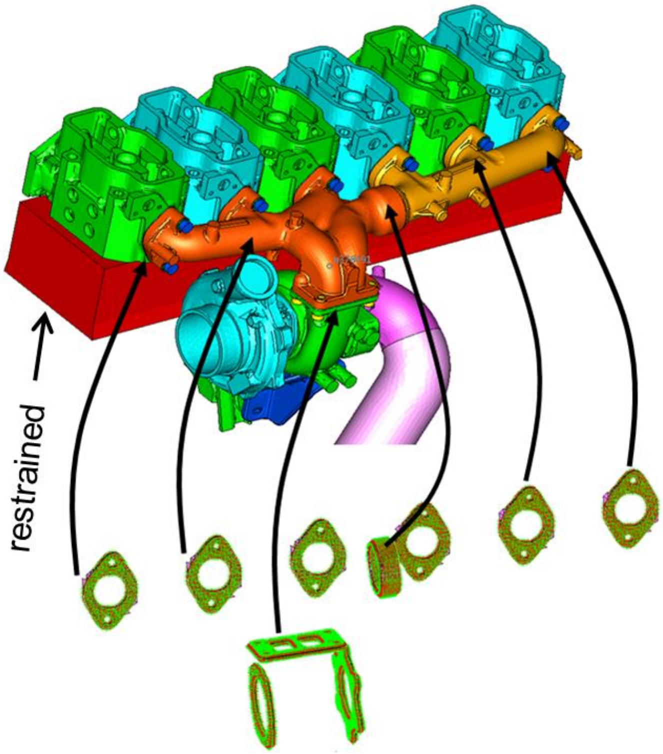

Figure 10.Contact regions on the FE model.

Loads

The main loads for thermomechanical analysis of exhaust manifold are the clamping forces introduced by bolts fastening and the material expansion–contraction due to temperature variation during the engine operation.

For LCF evaluation, stress and strain have been taken after four cycles applied on the exhaust manifold, as depicted in Figure 11. The internal gas pressure influence had been disregarded.

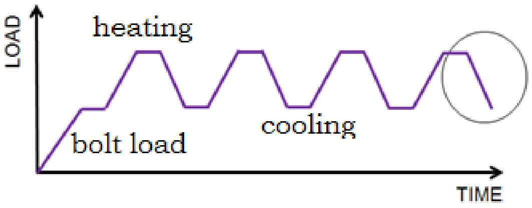

Figure 11. Schematic cyclic loading for exhaust system analysis.

Results

Heat transfer Results

The temperature field obtained from heat transfer analysis was shown in Figure 3. The maximum temperature on exhaust manifold is around 800^{o}C.

Stress-Strain Results

In the first step of stress-strain analysis the bolt fasten introduces local deformation over the exhaust manifold system, mainly around the bolt holes regions. By cycling the temperature from room load field to full load distribution, the bolt forces also varying and is an important variable to be monitored, in order to verify eventual opening between surfaces. In Figure 12 is illustrated a typical manifold bolt behavior. After the bolt clamping, the forces fluctuation is significantly on the traction side, indicating that the bolt forces are enough to stand the joint, i.e., there is no expected opening in such region.

Contact pressures shown in Figure 13 corroborate with the earlier statement. As one can see in that figure, there is no contact pressure lost in the manifold/cylinder head interface as well as in manifold/turbocharger interface.

The displacement of exhaust manifold is shown in Figure 14. There is a movement in the direction of cylinder head length. Both extremes (see the red circles) are dislocated, attempting to stretch the manifold. These displacements, however, are not enough to produce leakage, and also was considered under the acceptable limits.

Areas where plasticity occurs are shown in Figure 15. As shown, the equivalent strain is concentrated under the bolt heads and also areas with small fillets (region machined to place the washer).

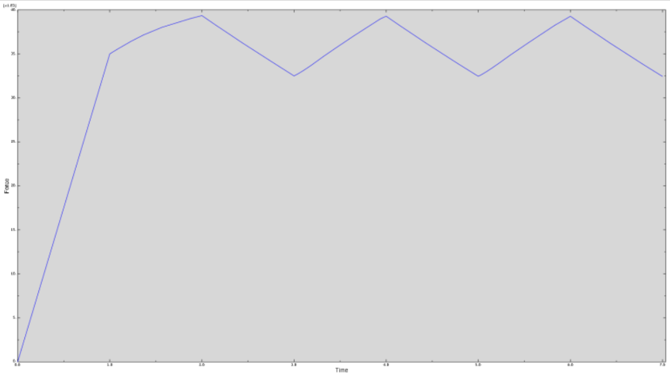

Figure 12.Typical force variation for manifold load.

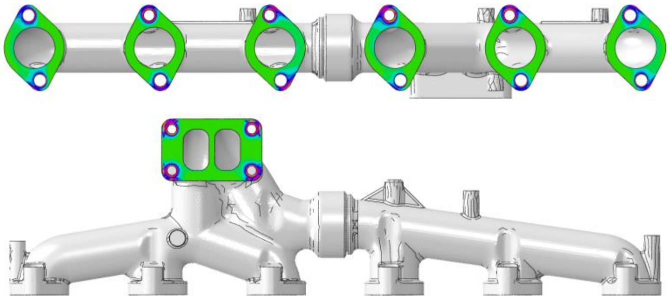

Figure 13.Contact pressure on the exhaust manifold/turbocharger interface.

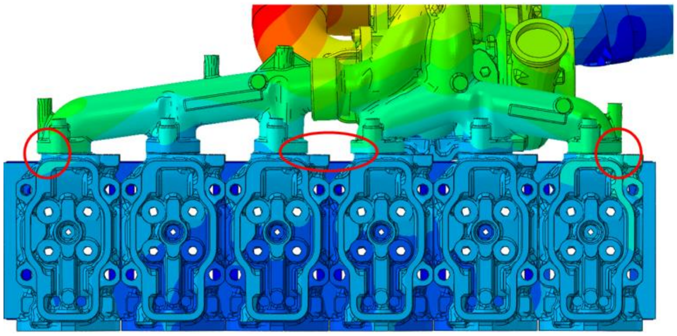

Figure 14.Axial displacement of exhaust manifold.

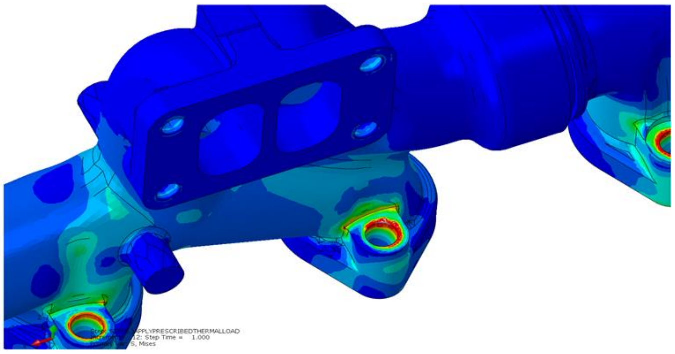

Figure 15.Equivalent plastic strain distribution on exhaust manifold.

Fatigue Damage Results

The estimated number of cycles for failure has been evaluated by equation (1).

For exhaust manifold, the distribution of estimated cycles to failure is shown in Figure 16. As expected from strain results, the critical areas also occur on the small machined fillets areas.

In Figure 17 is shown distribution of cycles to failure for turbocharger, where the worst regions also occurs on a small machined fillet area.

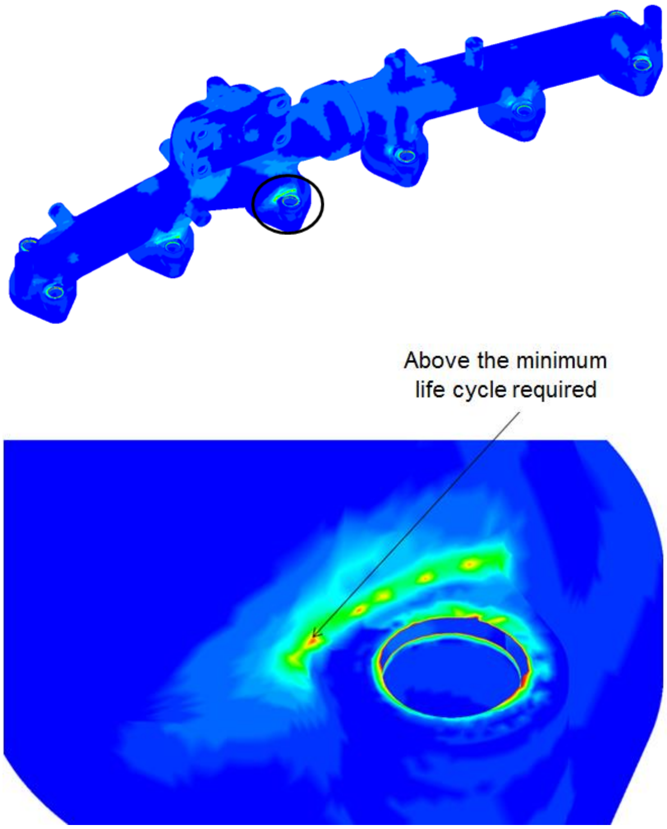

Figure 16.Number of cycles for failure on exhaust manifold.

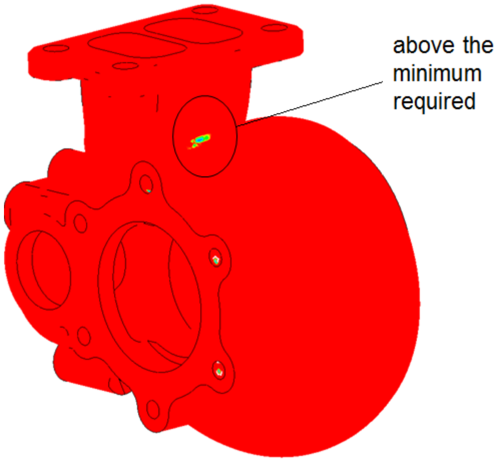

Figure 17.Number of cycles for failure on turbocharger.

Conclusions

In this paper, it is shown the estimation of fatigue life of exhaust manifold under thermo-mechanical loads. The damage calculation method includes only the mechanical damage, disregarding creeping and oxidation mechanisms.

The temperature field has been evaluated from 1D simulation and experimental measurement on the surfaces of manifold, turbocharger and elbow pipe.

Several areas in the exhaust manifold in which material plasticity occurs have been detected and the number of cycles estimated. The number of cycles estimated for the turbocharger has also been estimated. In both cases, the life estimation is above the minimum number of cycles required. Usually, in experimental tests the failure occurs between 1000 and 10000 cycles.

Finally, as bolt tensioning and contact regions are represented in the model, the actual slippage between the manifold and the cylinder head can be well estimated (see Figure 14). Gasket opening and gas leakage also can be approximated with the modelling herein employed.

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Appendix

The experimental measurement of temperature on the exhaust manifold system was performed during the engine running. An intermediate temperature distribution is depicted on Figure A1.

In Figure A2 is shown positioning of thermocouple to acquire the temperatures on bolts.

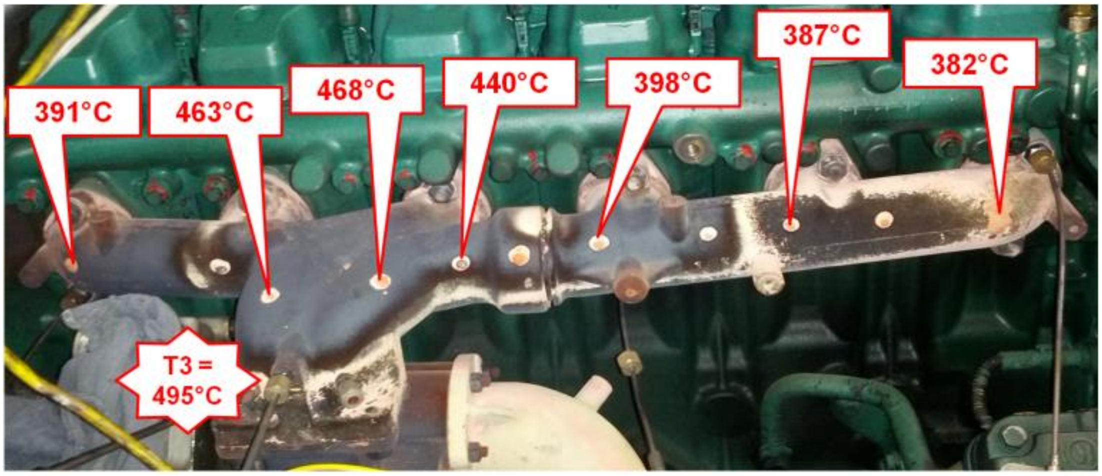

Figure A1.Intermediate(half load) temperature measurement on exhaust manifold.

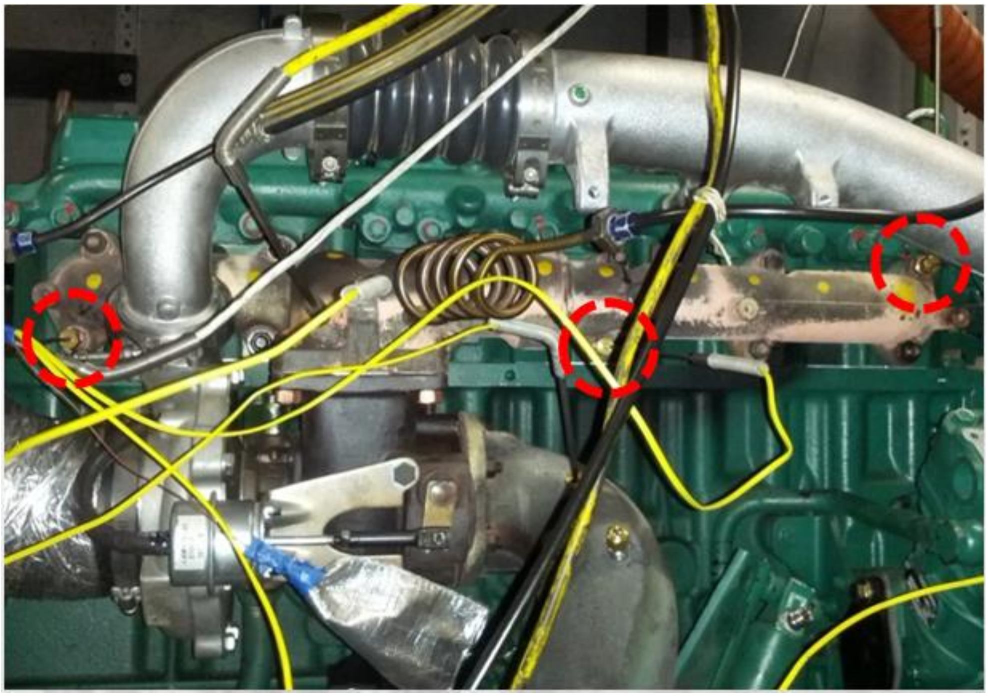

Figure A2.Thermocouples on exhaust manifold/cylinder head bolts.