

Fatigue Life Calculation under Thermal Multiaxial Stresses in EGR Coolers

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ABSTRACT

Recent emissions standards have become more restrictive in terms of CO₂ and NO_x reduction. This has been translated into higher EGR rates at higher exhaust gas temperatures with lower coolant flow rates for much longer lifetimes. In consequence, thermal load for EGR components, specially EGR coolers, has been increased and thermal fatigue durability is now a critical issue during the development.

Consequently a new Thermo-Mechanical Analysis (TMA) procedure has been developed in order to calculate durability. The TMA calculation is based on a Computational Fluid Dynamics simulation (CFD) in which a boiling model is implemented for obtaining realistic temperature predictions of the metal parts exposed to possible local boiling. The FEM model has also been adjusted to capture the correct stress values by submodeling the critical areas.

Life calculation is based on a Multiaxial Fatigue Model that has also been implemented in FEM software for node by node life calculation. This model takes into account the effect of temperature using the stresses obtained in linear elastic FEM analyses and the temperature dependent properties of the metal. Material Fatigue Properties have been obtained from an extensive test campaign with fatigue specimens for different materials and temperatures. To verify the proposed methodology several EGR cooler prototypes were tested under different thermal-stress cycles.

The results have shown good accuracy between the tests and the predicted life expectancy when using the methodology developed.

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INTRODUCTION

Since 60's emissions targets have been set by the Environmental Protection Agency (EPA) in United States, (CEPA) in Canada, (EU) in Europe, National Auto Fuel Policy in India, (MOE), (MLIT) and (METI) in Japan and by (SEPA) in China, among others. These regulations focus on nitrogen oxide (NO_x) and particulate Matter (PM) emissions reduction among others. Exhaust gas recirculation (EGR) is an emissions control technology that allows to NO_x emissions reduction from most types of diesel engines from light through medium and heavy duty engine applications. At this moment is being also used in gasoline engines for fuel consumption reduction.

EGR works by recirculating a portion of engine's exhaust gas back to the engine cylinders. In a gasoline engine, this inert exhaust gas improves the pumping losses dethrottling the engine, improves combustion phasing and also reduces enrichment. In a diesel engine the exhaust gas replaces some of the excess oxygen in the pre-combustion mixture. Because NO_x forms primarily when a mixture of nitrogen and oxygen is subjected to high temperature, the lower combustion chamber temperatures caused by EGR reduces the amount of NO_x the combustion generates. Most modern engines now require exhaust gas recirculation to meet emissions standards.

The EGR Systems main components are shown in Fig.1.



Figure 1. EGR systems main components.

Thermal Fatigue is a kind of fatigue caused by repeated heating and cooling, no internal stress is produced in a solid material if the temperature increase uniformly and the volume change is unrestrained. In a solid that is restrained so that it cannot expand (or contract) freely, a temperature change gives rise to a stress called a “thermal stress”.

Repeated heating and cooling in EGR system is produced by engine varying loads. These varying loads are translated into varying mass flow and temperature that cause the thermal stresses in the parts.

The most critical components of EGR system regarding thermal fatigue are the inlet EGR tube and the EGR cooler. EGR tube is not cooled and the skin metal temperature can reach high values (600-800°C). Thermal fatigue, creep and oxidation at high temperature can occur in this component. The EGR cooler is an air-to-liquid heat exchanger made of stainless steel that cools exhaust gas using engine coolant fluid. Coolant works typically in the range of 90-100°C and exhaust gas temperature is normally in the range of 500-850°C depending on the application. In consequence extremely high thermal gradients appear in the parts. Fig. 2 shows the deformed shape of an EGR cooler colored by temperature.

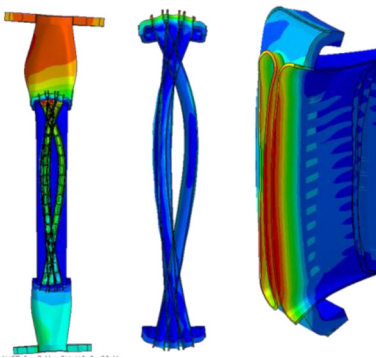


Figure 2. Deformed Shape colored by temperature.

One of the critical phenomena that are involved in this issue is coolant boiling. Boiling is the rapid vaporization of a liquid, which occurs when a liquid is heated to its boiling point. It occurs in three

characteristic stages, which are nucleate, transition and film boiling. Boiling itself is not an issue, and some authors recommend it because the use of boiling in engine cooling systems offers higher heat transfer. The drawback is that if film boiling appears, wall temperature increase drastically and the part fails very quickly. This happens when Critical Heat Flux (CHF) point is reached (Fig. 3).

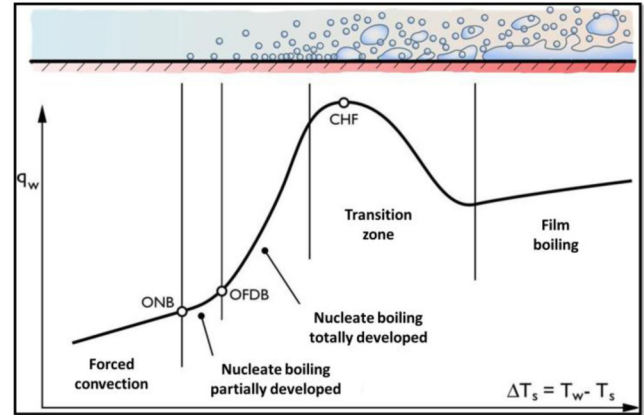


Figure 3. Boiling curve.

In consequence boiling affects thermal fatigue in two ways:

1. Below CHF nucleate boiling occurs, heat transfer is enhanced and metal temperature is limited.
2. When film boiling occurs, stresses in the part increase drastically causing an early failure.

Thermo-mechanical Analyses (TMA) are based on a Computational Fluid Dynamics (CFD) simulation in which metal temperature is predicted. Common single phase CFD calculations without boiling model can only give good results in those areas in which coolant doesn't boil. Critical areas in an EGR cooler are subjected to high heat transfer, so boiling occurs. In consequence, a boiling model is necessary to obtain a realistic temperature map for predicting correctly the thermal expansion and thermal stresses in an EGR cooler.

Previous investigations [1; 2] have been done in this field revealing its high complexity. Generally these works are based on commercial boiling models already implemented in commercial CFD software and in non-linear FEM calculations using visco-plastic material models. Non-Linear FEM calculations based on Chaboche or Cailletaud models needs several parameters for adjusting material visco-plastic behavior and really high computational cost.

The present work means an optimum solution among quality, cost and deadline. CFD boiling model has been developed and adjusted to fit actual metal temperatures in the components of this investigation without increasing calculation time. Linear FEM analysis are quick calculations that don't need very complex non-linear material models adjusted with expensive and time-consuming tests. Multiaxial Fatigue model estimates life expectancy from linear stress using material fatigue properties obtained with isothermal fatigue tests.

ANALYTICAL CASE: TMA

Modeling Strategy

The Thermo-Mechanical Fatigue (TMF) life prediction methodology presented in this work is based on a simulation path whose main milestones are (i) cycle characterization (boundary conditions), (ii) thermal map by means of a CFD with an embedded boiling model, (iii) structural analysis by means of FEM, (iv) material and prototype testing and (v) fatigue modeling.

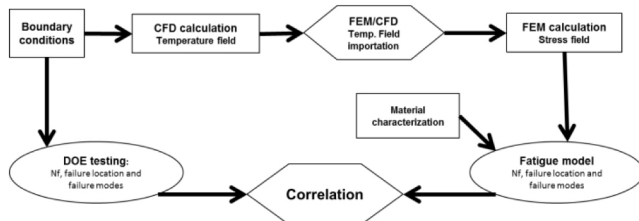


Figure 4. TMA analysis and correlation work flow.

The first step in the procedure is to analyze the cycling conditions of the test to select the boundary conditions that best fit the thermal stresses that the system will undergo. Fatigue failure is caused by an alternating stress between 2 working points with different load. In Fig. 5 it is represented the alternating metal temperature during thermal cycling. In this work, it is assumed that $\frac{\Delta \varepsilon}{2}$ is mainly produced by the difference between those points and no transient effects occur in between. In consequence the TMA analysis must take into consideration hot stage and cold stage of the thermal cycle, that is, to obtain the stress tensor in both points and calculate afterwards the alternating stresses.

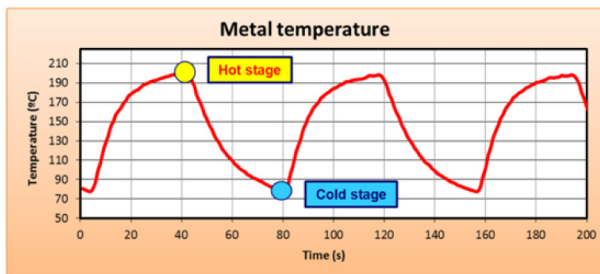


Figure 5. Metal temperature during thermal cycling.

Based on the boundary conditions established, a single-phase CFD simulation of the whole system including gas and coolant circuits is performed for hot and cold stages. Liquid temperature dependent properties are extrapolated to capture temperature effects without considering phase change. The CFD solution at this first stage is checked to verify the main hypothesis of the simulation including grid size and resolution on critical areas, boundary conditions, etc.

Once the single-phase CFD model has been computed, the next step is to include local boiling effects. This is done by the introduction of an user-defined boiling model fully embedded into the commercial CFD software by means of the User Defined Functions (UDF). With the use of this model, the accuracy in the prediction of the temperature of the component is increased by the introduction of an overall heat transfer enhancement when the boiling regimen is locally achieved at certain locations of the component.

Once the complete CFD model has been solved and hence a thermal map of the cycling conditions has been obtained, the CFD results of the solids are transferred to the FEM software by means of an external ad-hoc procedure employing ASCII files containing the local heat transfer coefficient and bulk temperature of each coordinate of the solid surface of the system. The thermal map obtained for each point of the cycle is then imported in the FEM software, which interpolates the local heat transfer coefficients and bulk temperatures in the FEM grid to transfer the thermal loads estimated by the CFD.

The mechanical loads and ties are also applied to the global model of the EGR cooler. Grid size, elements and ties between components have been adjusted in the FEM model to obtaining the correct stress field. Some critical areas of EGR coolers are the junction between inner tubes and header due to notch effect, and submodelling is necessary in these areas for obtaining realistic stress values.

Linear structural FEM calculations estimate the linear stress values. Elasto-plastic strain and stress values are inferred then using Neuber's rule. Thermal Fatigue in EGR coolers is mainly related with Low Cycle Fatigue (LCF). LCF failure is associated with the presence of cyclic plastic strains at stress concentration points within the component. The initial step in the calculation procedure is thus the determination of these cyclic plastic strains. For this, we use a generalization of the well-known Neuber's rule for application to multiaxial proportional cyclic load, as described further down.

Finally it is applied the multiaxial fatigue model for life assessment. It is well known that fatigue scatter is great, surface finish, mechanical processes and thermal treatments that base material suffers have deep influence on material fatigue properties. The case presented in this work is related with EGR coolers that are submitted to brazing metal-joining process. During brazing process the whole EGR cooler passes through a furnace at high temperature. It is thus imperative to make a fatigue characterization of the metal sheet after this brazing process. Austenitic and ferritic stainless steel grades were characterized using standard specimens with isothermal uniaxial tests at different temperatures in order to obtain the fatigue properties after a representative brazing furnace heat treatment.

In order to adjust this methodology, a test correlation matrix was defined. This matrix took into account several geometries, materials and working conditions in order to sweep all the possible EGR cooler configurations and working conditions. Fig. 6 shows the basic design of EGR cooler that was selected, representative of actual designs.

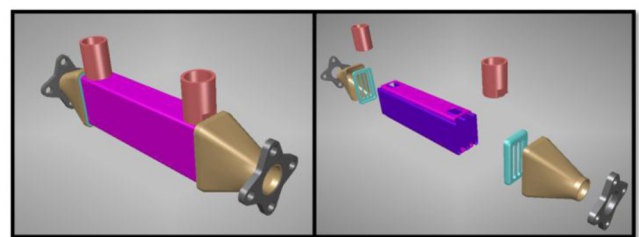


Figure 6. EGR cooler basic design.