Anisothermal energetic approach to predict thermomechanical fatigue lifetime on exhault manifold

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Abstract Numerical simulation is more and more used in automotive industry to reduce design time and cost. The estimation of adapted fatigue criteria based on few experiments is thus an important challenge. This paper focuses on the difficulties to identify an anisothermal LCF criterion reliable on a large range of temperature. Experience of car maker Renault is presented and illustrated by an application on a stainless integrated turbo manifold.

1 INTRODUCTION

The field reliability of exhaust manifold is still a very active applied domain in automotive industry due to recent technological evolutions (materials and architectures) and the need to reduce design and development costs.

Actually the adaptation to worldwide markets and the emission standards generate an increase of thermal loadings on the engine exhaust system.

The exhaust manifold is the first component of the exhaust system as it connects the cylinder head exhaust face with the turbocharger. Consequently, the increase of thermal loadings affects directly the exhaust manifold. These loadings are cyclic because of the variations of the engine power, and therefore create thermomechanical stresses and then low cycle fatigue cracks.

In order to reduce design and development costs, it is crucial to develop a (robust) numerical lifetime approach. That approach should be based on:

- the identification of the material behavior and a fatigue criteria,
- an adapted finite element methodology dedicated to estimate the thermomechanical damage generated by anisothermal cycles on engine test bench.

The purpose of this paper is to describe the methodology used to estimate thermomechanical damage due to anisothermal cycles applied to the austenitic stainless steel 1.4826Nb. To explain our approach, the section 2 presents a review of several energetic approaches that historically were used to obtain a thermomechanical fatigue criterion and to predict lifetimes. In section 3, the reserved anisothermal energetic-based criterion is presented. Section 4 and 5 deals with the interest of that approach on lifetime's predictions.

2 FROM SPECIMEN TO STRUCTURE: IMPROVEMENTS OF RSA'S FATIGUE MODEL

During the past ten years, a great diversity of exhaust manifold materials has been characterized, for an important variability of temperature in use (between 400°C to 950°C).

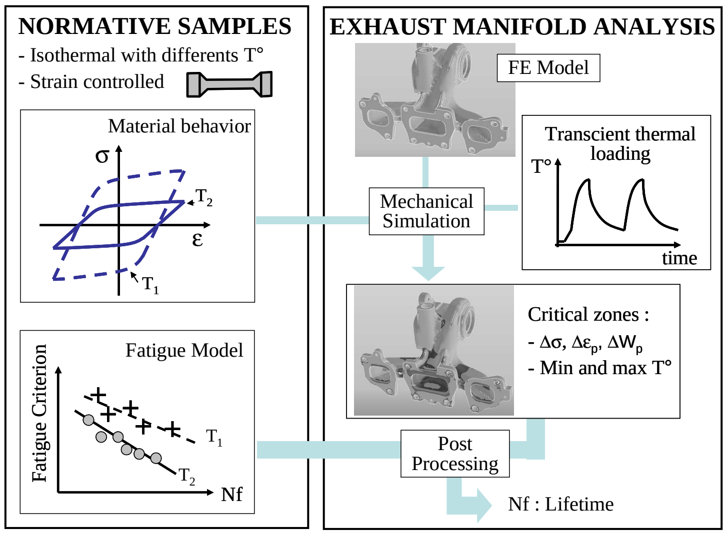


Figure 1. Global methodology from specimen to structure

Tests on normative samples (LCF tests) are done with various strain amplitudes, at different fixed temperatures. They allow us:

- to identify the parameters of the material behavior, depending on the temperature,
- to estimate the best fatigue model (regarding their ability to predict the results of those tests and their complexity).

In each new material characterization, we tried to compare the 3 main families of oligocyclic fatigue models based on: the amplitude of the plastic strains (Manson Coffin), the amplitude of the stresses (Lemaître Chaboche) and the energetic density variation (Charkaluk).

Kharkhour and Morin [1] proposed for a cast iron material, an energetic approach to predict lifetime:

$$Nf = K\left(\Delta W_p + \alpha_e \Delta W_e^{\,+}\right)^A \qquad (1)$$

where:

- ΔW_p represents the plastic dissipated energy density per cycle, responsible for the microcrack initiation,

$$\Delta W_P = \int_{cycle} \sigma : \dot{\varepsilon}_p \, dt \qquad (2)$$

- ΔW_e^+ the positive part of elastic energy dissipated, responsible for microcrack propagation,
- A and K two constants independent from the temperature.

The isothermal criterion leads to a very simple post processing of FE calculations. We only have to extract from a stabilized cycle the both dissipated energies (plastic and positive elastic part) and then to estimate the number of cycle until failure by the relation (1).

However, that approach, applied to high temperature material brings 2 main problems:

- Regarding the LCF experimental tests, we observe an almost perfect log correlation between ΔW_p and ΔW_e^+. To use an elastic energy part, we should change our tests procedure.
- For some materials we notice a temperature dependency of the 2 parameters A and K. As displayed in the next figure, it is not possible to group together all the levels of temperature.

  Nonetheless, for each temperature, a linear agreement is obtained between $\ln(N_f)$ and $\ln(\Delta W_p)$.

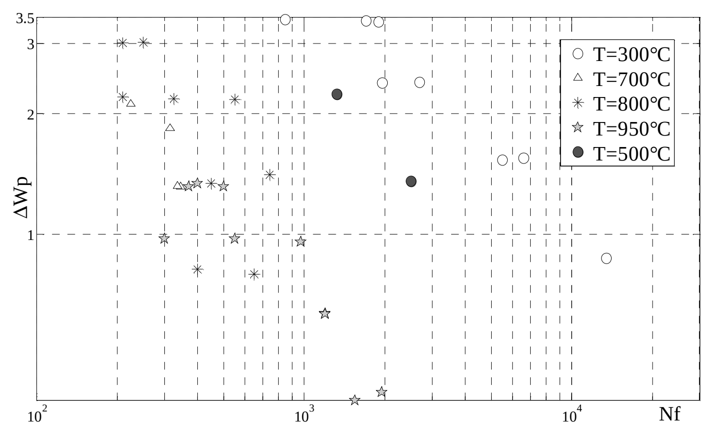


Figure 2. LCF tests of the austenitic stainless steel

For those reasons, an improvement was to consider alternative temperature dependent models:

- By grouping respectively low and high levels of temperature

Two isothermal Charkaluk models $Nf_1 = K_1(\Delta W_p)^{A_1}$ and $Nf_2 = K_2(\Delta W_p)^{A_2}$ are estimated for low ($T \le T_1$) and high ($T \ge T_2$) temperature.
The continuity of the lifetime model for $T_1 \le T \le T_2$ is ensured by the relation:

$$Nf = (Nf_1)^{1-\beta} \times (Nf_2)^{\beta} \text{ with } \beta = \frac{T - T_1}{T_2 - T_1} \tag{3}$$

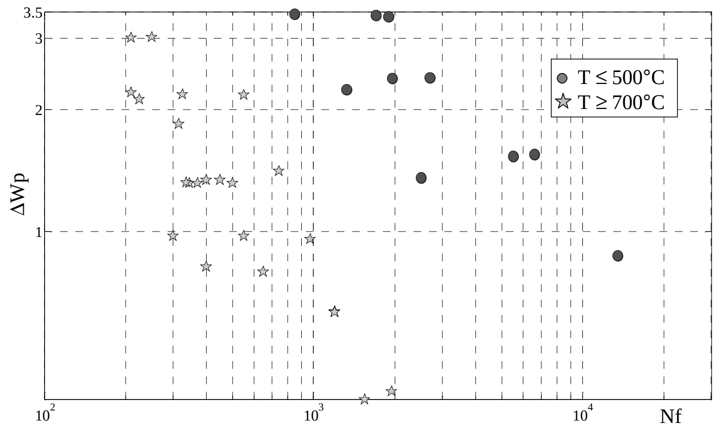


Figure 3. Grouping low and high temperature for bi-temperature model

That kind of model is more accurate and the dispersion of estimated lifetime decrease. Nevertheless, for some materials, and especially our austenitic stainless steel, this bi-temperature dependency is not sufficient to fit correctly the LCF test results.

- By assessing (or not) a temperature dependency of the 2 parameters A and K (such as A and Log(K) monotonic affine function of temperature)

$$Nf = K(T)\left(\Delta W_p\right)^{A(T)} \tag{4}$$

The last 2 models are typically anisothermal. They are based on a mechanical theory but also on empirical observations as shown previously.

Mathematical algorithms (such as maximum of likelihood) allow to estimate properly the coefficients and the dispersion of those lifetimes' models.

But what is it of its use on anisothermal loadings such as those encountered on engine tests? We deliver you our experience on this topic in the following chapters.

3 USING ANISOTHERMAL MODELS ON ANISOTHERMAL LOADINGS

To illustrate the difficulty encountered, let us consider the following general formulation (4) and the thermo-mechanical loading shown on figure 4.

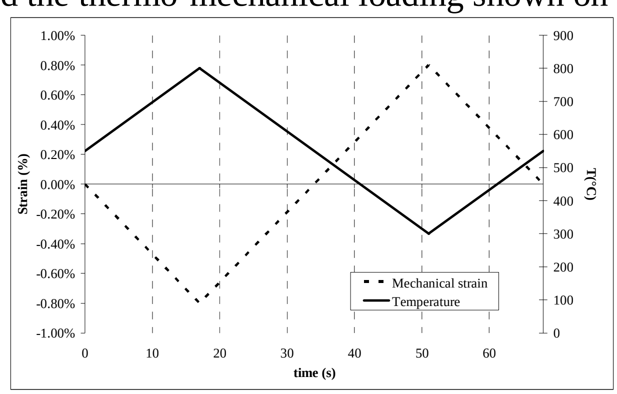


Figure 4. Example of thermo-mechanical loading

A straight forward exploitation of the model described in (4) is possible by identifying an equivalent temperature T_{eq} over the cycle and by estimating the lifetime by:

$$Nf = K(T_{eq})\left(\int_{cycle}\sigma:\dot{\varepsilon}_p dt\right)^{A(T_{eq})} \tag{5}$$

To not underestimate the lifetime, a common approach is to consider the parameters A and K at the maximum of temperature during the cycle, called T_{max} Charkaluk approach thereafter.

However, is it possible to exploit this model to take into account the evolution of the parameter (and so the damage) with the temperature over the cycle?

The idea is based on the definition of a "normalized" plastic energy defined as follows:

$$\Delta W_p^{norm} = \left(\int_{cycle}\frac{\sigma:\dot{\varepsilon}_p}{\sigma_N(T)}dt\right) \tag{6}$$

Using the normalized ΔW_p^{norm}, the modified model can be written as:

$$Nf = K_n\left(\Delta W_p^{norm}\right)^{A_n} = K_n\left(\int_{cycle}\frac{\sigma:\dot{\varepsilon}_p}{\sigma_N(T)}dt\right)^{A_n} \tag{7}$$

In this expression, the parameters A_n and K_n are chosen in order to fit the master curve and are no longer temperature dependent.

Such a procedure can only be used if a particular set of $\sigma_N(T)$ coefficients can be found for which all experimental points at various temperatures do align on a single master curve in the $\left(\log(\Delta W_p^{norm}),\log(N_f)\right)$ diagram.

Figure 5. shows that the previous assumption is reasonably well defined in the case of the austenitic stainless steel used in this study.

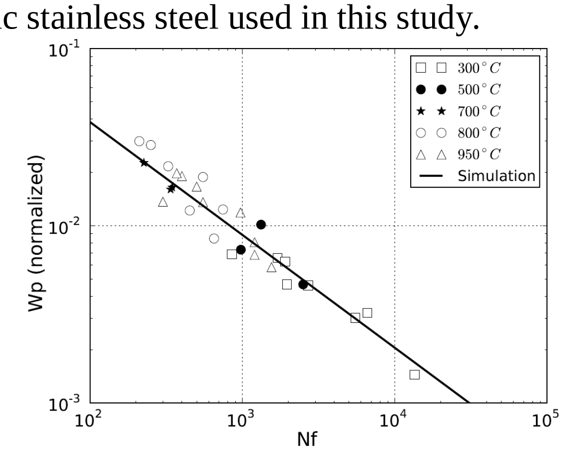


Figure 5. Normalized Charkaluk fatigue model calibrations results

Note that a good initial guess for $\sigma_N(T)$ is to use UTS of this particular temperature. This particular choice may be updated in order to obtain a best fitting of data points around the master curve.

4 NUMERICAL APPLICATION ON SAMPLE SIMULATIONS

To illustrate the temperature dependency in the proposed model, we consider the cyclic loading described in Figure 6.

The cycle is strain-controlled, defined by a symmetrical triangular unloading loading function with an amplitude of $2\sigma_{max}$ (Figure 6(a)). Different temperature variations during the cycle are applied (Figure 6(b)).

For convenience purpose, a temperature variation is indexed by its normalized slope f.

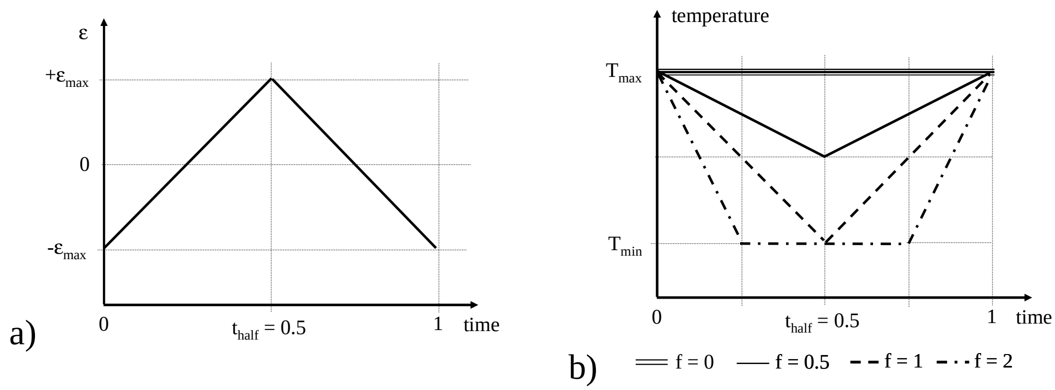


Figure 6. Mechanical (a.) and thermal (b.) loading used in the anisothermal case

The above described loading is used to simulate the stress-strain loop with an elasto-plastic behaviour with nonlinear isotropic and kinematic hardening using Z-sim the material simulator tool of the Z-set software suite.

Each stress-strain loop along with the parameters (A_n, K_n) gives a life time prediction for the each corresponding temperature slope f. The results are displayed in the Figure 7.

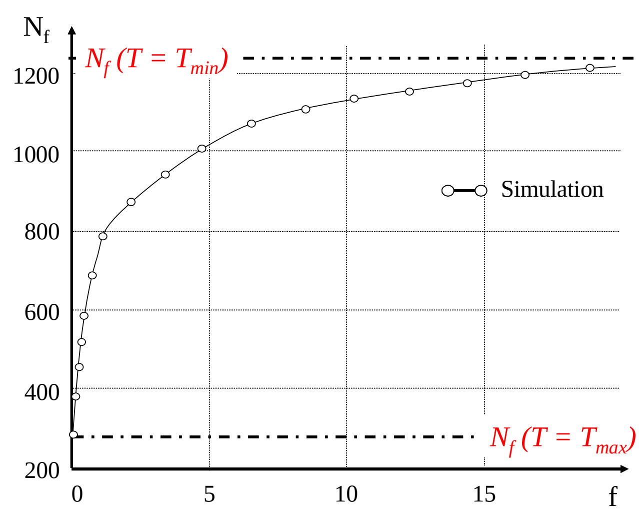


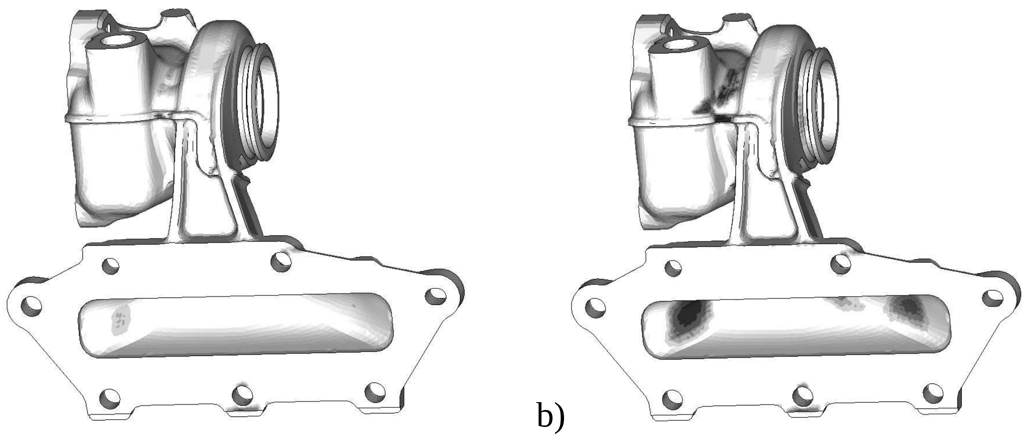
Figure 7. Life time prediction N_f as a function of the normalized slope f

The isothermal life time prediction for the T_{min} and T_{max} gives upper and lower bounds and all other cases fall in between. Note that in all cases, this anisothermal procedure yields higher N_f values than the too strongly conservative T_{max} Charkaluk approach.

5 BENEFIT OF THAT APPROACH ON STRUCTURAL ANALYSIS

Variations of the engine power induce thermo-mechanical loading that can be represented as shown on figure 1.

We have compared the result of lifetimes post treatment of the both approach: the T_{max} Charkaluk approach and the normalized Charkaluk. Black part of the FE model represents low level of N_f values.

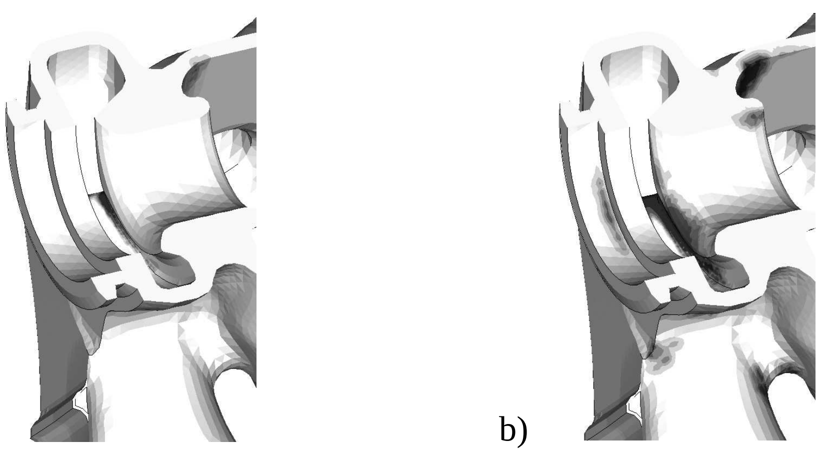


a) b)

Figure 8. Normalized (a) and T_{max} Charkaluk (b) lifetimes post treatment

T_{max} Charkaluk approach is very conservative; it shows many areas that do not cause any fatigue problem during engine tests bench.

Normalized Charkaluk approach only focuses on the weak areas of the integrated turbo manifold.



a) b)

Figure 9. Normalized (a) and T_{max} Charkaluk (b) lifetimes post treatment

The same observation is made in the inside turbocharger areas. The weak areas are revealed and the T_{max} Charkaluk approach is far too conservative.

The next table illustrates, for several areas the lifetimes obtained for the both post processing.

Table I. Comparison of predict lifetimes regarding the 2 post processing

Area	Normalized Charkaluk	T_{max} approach
1	1100	370
2	2800	1100
3	10000	1700
4	5800	1000

Charkaluk T_{max} post processing gives N_f between 2 to 8 times smaller than the normalized Charkaluk ones.

6 CONCLUSION

Isothermal oligocyclic tests on normative sample reveal relatively strong dependency of the lifetime model from the temperature of Charkaluk parameters. Thus, normalization of plastic energy density is a consistent way that overcomes the dependency of the scaling parameter.

The main benefice of the new criteria and of its implementation in FEA software is the ability to treat any kind of thermal loadings consistently without making rough hypothesis.

We applied this method on an engine application with an austenitic stainless steel material. The comparison between previous and new methods reveals that the normalized Charkaluk is less conservative.

The benefit is important in the context of the reduction of the development and design costs in automotive industry.

7 REFERENCE

1. E. Charkaluk and A. Constantinescu, An energetic approach in thermomechanical fatigue for silicon molybdenum cast iron, Material at High Temperature, 17(3), 2000, 373-380.

2. H. Kharkhour and G. Morin, Thermal fatigue of exhaust manifold, 26e Journées de Printemps de la SF2M, 2007.