NUMERICAL APPROACH IN THERMOMECHANICAL FATIGUE

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ABSTRACT

This paper presents a global approach of thermomechanical design in the automotive industry based on four different aspects : the loading definition, the modelling of the constitutive law and of the damage and a failure criterion. This approach is applied on cylinder heads and on exhaust manifolds submitted to transient thermal loading and permits to predict the cracked area as well as the lifetime. The main hypothesis and the different aspects are detailed and results on automotive parts are presented.

1 INTRODUCTION

The study of metallic structures submitted to high temperatures began really in the 50's with the development of the aeronautic industry and with the development of the nuclear power stations. Metals were then submitted to temperatures higher than half the melting temperature, where mechanical characteristics are significantly modified and numerous damage mechanisms are encountered. Thermomechanical loadings induce then often inelastic cyclic strains on the structures.

Metal fatigue studies came then from the high cycle domain to the low cycle one. Many research were realised on this topics : understanding and modelling of the physical phenomena, development of constitutive laws, development of high temperature test rig, …

In the same time, numerical computation became more and more efficient and permits simulations of complex loadings, but structures submitted to thermomechanical loading inducing multiaxial stress and strain states were not extensively studied. In the automotive industry, predictive method for such structures are necessary to limit the number of physical prototypes and then the development time of components.

A design approach is based on four particular aspects : the loading definition, the modelling of the material behaviour and of the damage under cyclic loading and the definition of the failure of the structure. The loading associated to the material behaviour provide the mechanical response of the structure and this one permits the determination of the lifetime through a damage indicator, lifetime depending of the failure criterion.

Two particular automotive components are concerned in this paper : aluminium alloy cylinder heads and cast iron exhaust manifolds. The thermomechanical loading corresponds to the start and stop cycles of the engine. In a first part, main hypothesis and choices necessary for the global approach are detailed. Then, the application of those choices in the design method are presented : the prediction of lifetime of complex structures submitted to thermomechanical loading is possible as soon as geometry is known.

2 A GLOBAL APPROACH IN THERMOMECHANICAL DESIGN

2.1 Loading definition

The structure is essentially submitted to a thermal cyclic loading representing the start and stop of the engine and the mechanical part of the loading is static. Thermal loading definition is a key feature of the design approach because the accuracy of the thermal loading determines the accuracy of the mechanical response of the structure and then the lifetime [1].

2.2 Mechanical behaviour

Lot of works were realised in France on viscoplasticity coupled with damage (continuum damage mechanics) during the 70's with Lemaitre and Chaboche [2]. However, this type of approach has some drawback: the complexity of the models with a lot of temperature dependant parameters, the complexity of the tests and of the calibration of the parameters and large time computations induced by the coupling. Results of Sermage et al. [3] shows that this coupling is often not necessary.

For all those reasons, this approach uncouples damage and material behaviour. The constitutive law is viscoplastic with a linear kinematic hardening and the parameters (5 or 6 per temperature) are identified on the stabilised cycle of the characterisation tests. The numerical implementation used a totally implicit algorithm which permits large time increment and relatively small computation time.

2.3 Damage

Many parameters influence the damage mechanisms in thermomechanical tests : temperature, mean stress, mean strain, dwell time, … To assess the lifetime of structures, two different ways are possible. The first one consists in parametric approaches which gives a direct relation between lifetime and mechanical and/or physical parameters, like Manson-Coffin law [4, 5] for example. The second way is based on the continuum damage mechanics initially developed by Rabotnov on creep damage. Creep-fatigue interaction laws were then developed by Chaboche [6] for the aeronautic industry. As previously mentioned, those laws are complex and require many tests to identify the temperature dependant parameters.

For this reason, parametric laws seem to be preferable for their simplicity but require the determination of physically based damage indicators consistent with the multiaxial state of stress and strain in the structures and independent of temperature.

2.4 Failure criterion

The last aspect concerns the definition of a failure criterion. The objective of the design in the automotive context is to avoid a macroscopic - i.e. at an engineer scale - crack initiation which can conduct to a fault in the engine during the lifetime of the vehicle. As long as a crack is confined in an elementary volume of material, its propagation is governed by the local mechanical fields. As soon as its size becomes greater than this volume, its propagation is governed by the structure. This is the definition of a failure in our context.

In this approach, initiation and propagation are not studied separately; the failure is defined at the scale of the structure and in the same manner for a specimen, a cylinder head or an exhaust manifold.

3 MECHANICAL MODELLING OF THE MATERIAL IN THE STRUCTURE

3.1 Context

The modelling of the material behaviour has to be realised with the objective of a structural computation. Therefore, the key feature of the modelling is to be representative of the material *in* the structure, this implies a choice of representative tests conditions (temperatures, loading rates,…) as well as representative specimens (microstructure, process, …). This is a crucial part of the characterisation and the modelling. Different type of uniaxial tests are used for the characterisation of the model and the calibration of its parameters: isothermal monotonic tests (tension, creep), isothermal cyclic tests at different strain rates and non isothermal cyclic tests. To validate the models and the calibration in a multiaxial non isothermal context, tests on simple structures are necessary. For example, thermal fatigue tests are realised on specimen submitted to thermal cyclic loading by Joule effect. Then, tests on components (thermal shock) can validate the complete approach of design. This requires controlled and known test conditions which is not simple because of the complexity of an engine bench test. This particular point will be detailed in the case study.

3.2 Constitutive law and calibration of parameters

The studied structures, in cast iron for the exhaust manifolds and in aluminium alloy for cylinder heads, are submitted to thermomechanical cycles between the room temperature and a maximal one close to 0,3 to 0,5 the melting temperature (typically 800°C for the cast iron and 300°C for the aluminium alloy). In this range of temperature, the material, plastic at low temperature, becomes viscoplastic as the temperature increases.

The modelling of the constitutive law has to integrate this phenomenon. Therefore, different models can be used : a classical viscoplastic model with only one inelastic strain similar to those developed by Chaboche [2] or a two layer viscoelastic-elastoplastic model which permits to have two inelastic strains, viscous and plastic [7]. In our studies, both models were used and compared

The main difficulties of viscoplastic constitutive laws are the multiaxial translation of the equations and the numerical implementation in a FE code like ABAQUS/Standard. For both viscoplastic models presented above, an implicit scheme was chosen which permits large time increments and a stability of the computed mechanical response of the structure [7].

The other difficulty is encountered with the calibration of the models parameters. The classical way consists in an identification at each tested temperature and a linear interpolation between the identified temperatures. Verger et al. [8] showed that non isothermal tests are necessary for the calibration because of the parameters coupling of such models of viscosity (Norton-Hoff laws). As models are implemented and parameters are identified, structural computations are possible.

3.3 Damage modelling

The damage under thermomechanical cyclic loading is modelled with an energetical approach. Indeed, the dissipated energy density per cycle (plastic work) is one possibility to define the damage in this context. Results coming from literature were synthesised by Verger el al. [9] and presented plastic work versus the number of cycles to failure for different material at different temperatures. The same trend as Halford's results [10] was observed. For particular steels, temperature seems to have an influence on the results. However, it was shown that the positions are also close for the studied cast-iron [11]. Similar results have been obtained for aluminium [12]. Let us now remark that the dissipated energy per cycle can be extended to a multiaxial load path as:

$$\Delta w(x) = \int_0^T \sigma(x,t) \cdot \dot{\varepsilon}(x,t) \cdot dt$$

where σ and ε are stress and strain tensors, T the cycle period. Moreover the obtained function is not explicitly temperature dependant and can therefore easily integrate a non isothermal approach. More details are given in [13] which show that this criterion can be simply used on numerical simulations.

4 CASE STUDY

4.1 Materials and tests

The studied materials are:

- a spheroïdal graphite cast iron with molybdenum and silicon addition named SiMo cast iron. This material is used in the case of the exhaust manifolds.
- a A356 aluminium alloy (with silicon and magnesium addition) with a thermal treatment T7 used for the cylinder heads.

Different type of fatigue tests were realised on specimens and on components:

- isothermal strain controlled LCF tests at different temperatures between 100°C and 700°C for the cast iron and between 100°C and 300°C for the aluminium alloy. The strain rate was 10^{-3} s^{-1} for all tests and the different total strain ranges were taken between ±0,25% and ±1%.
- thermal fatigue tests corresponding to the figure 1. The maximal temperature, obtained in the middle of the specimen, varied from 40°C and 700°C in the case of the cast iron and between 75°C and 300°C in the case of the aluminium alloy. The spatial gradient was approximately 30-40°C/mm and the heating rate was approximately $20°C.s^{-1}$ for the cast-iron and $7{,}5°C.s^{-1}$ for the aluminium alloy (see [1] for more details).
- engine bench tests on components (thermal shock). Those tests are realised for the validation of all the engine (cylinder head, crankshaft, exhaust manifold, …) under thermomechanical loading corresponding to the start and stop cycles. One of the difficulty consists in the detection of the cracks as soon as they appear (macroscopic initiation), when this detection is possible.

4.2 Results

The LCF tests permit to construct the design curve, based on the energetic criterion. The numerical results obtained from the simulation of the thermal fatigue tests and of the thermal shocks are then compared with this design curve (see figure 3). The approach consists in the analysis of the stabilised response of the structure as this response can be considered representative of the total cyclic damage during all the test [11].

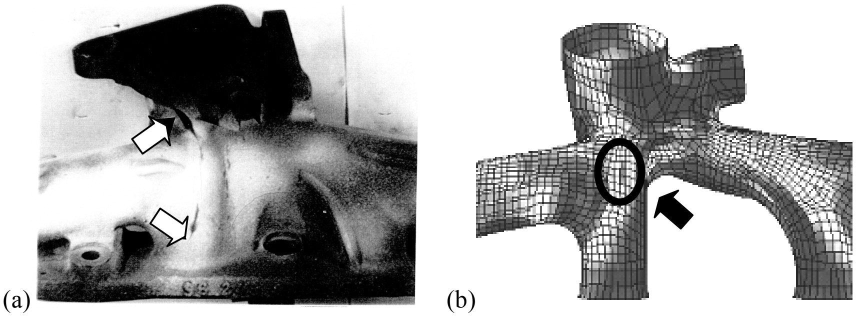

Figure 1: results on exhaust manifolds. The numerical simulation (b) indicates an initiation on the inner shell of the component. The experimental results (a) shows the final macroscopic crack.

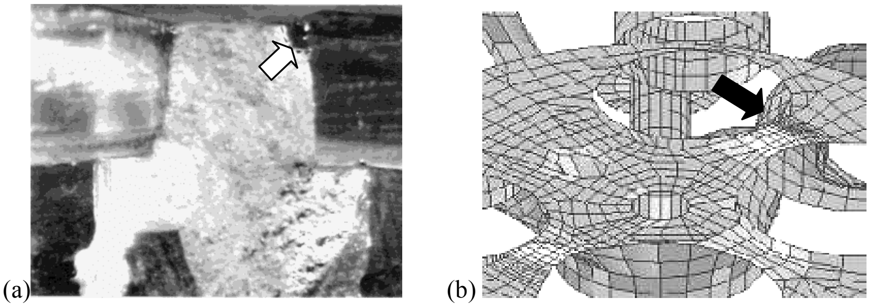

Figure 2: results on cylinder head. The crack initiates in the intervalve bridge (a) and this area is detected by the numerical simulation (b).

On figure 1 and 2, the cracked area observed after the tests on components are compared with the predicted cracked area. A good prediction can be denoted on exhaust manifold as well as on cylinder head. It can be underlined that simple stress analysis (von Mises) or strain analysis (plastic strain range) do not permit such a prediction [1]. Moreover, on the figure 3, one can observe a good agreement between the experimental and estimated lifetime for both type of tests on specimen and on automotive parts. This shows the great interest of this approach in thermomechanical design of complex structures.

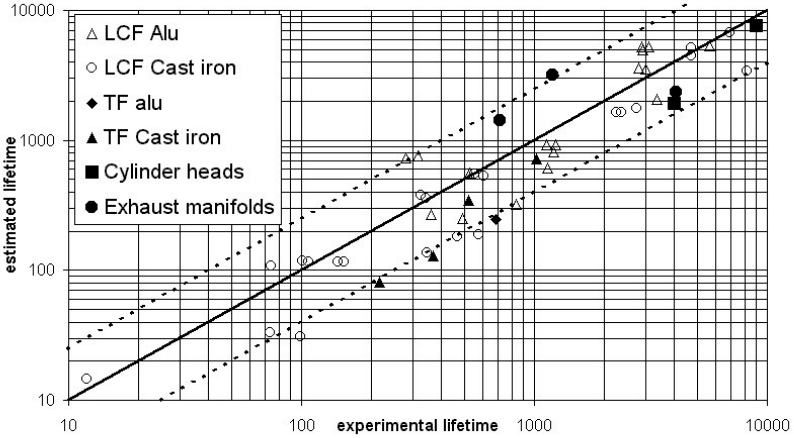

Figure 3: comparison between estimated and experimental lifetime on specimen and on components. Three type of results are synthesised : isothermal LCF tests on specimen, thermal fatigue (TF) tests on specimen and engine bench tests (thermal shock) for exhaust manifolds and cylinder heads.

CONCLUSION

This paper presents a global approach of thermomechanical design in the automotive industry based on four different aspects : the loading definition, the modelling of the constitutive law and of the damage and a failure criterion. This approach was applied on cylinder heads and on exhaust manifolds submitted to transient thermal loading and permitted to predict the cracked area as well as the lifetime of such structures. This is an important step in the design of structures submitted to multiaxial thermomechanical fatigue.

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