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ONERA's Multiaxial and Anisothermal Lifetime Assessment for Engine Components

This paper presents the calculation methods developed at ONERA to assess the lifetime of aeroengine structures subjected to multiaxial thermo-mechanical loadings. The complexity of the steps required in this process has grown over the past years, in order to take advantage of extremely accurate observations in materials and more precise experimental results. The research activities in the field of fatigue are presented within a framework that covers microstructural observations, mechanical testing, the development of constitutive equations and fatigue damage models associated with numerical calculations. All of these steps are today closely interrelated in the complex analysis of lifetime predictions. A fundamental aspect is highlighted: the simultaneous consideration of multiaxial and anisothermal loadings, which requires specific developments. These points are detailed, illustrated by many examples of applications and positioned with respect to research works in the literature.

Introduction

The lifetime prediction of complex structures, such as the high temperature components of aircraft engines is a critical step in the design process. Despite the number, the complexity and the effectiveness of existing lifetime assessment models in the literature (see the reviews of [32, 76, 66, 47 and 8]), none of them is far from unanimous. Effectively, these models must be integrated into a lifetime analysis workflow and require a consistency between the determination of mechanical fields in the component and the use of these fields in the fatigue model.

This workflow, schematically detailed in figure 1, is divided into several sequential steps, as generally admitted for metallic materials. It starts with the observation and the characterization of the material microstructure at the finest scales (grains, dislocations, precipitates etc.).

This first stage, conducted in parallel with some mechanical characterization tests, is essential to propose constitutive equations reproducing the observed phenomena. This formalism can be described by a purely phenomenological macroscopic approach [11] or by some multi-scale approaches [46], whose complexity will depend on the local phenomena to be taken into account regarding the effects of the microstructure and the dissipation mechanisms observed at this local scale. The third step consists in computing the component using the constitutive equations by the finite element method, in order to determine all of the stabilized mechanical fields (stresses, strains and internal variables) and then to predict the lifetime with the adequate fatigue damage model. In our analysis, the lifetime is related to the number of cycles before the detection of the macroscopic crack initiation with a conventional experimental device. Once the crack initiates, further analysis consists in following the crack propagation as a function of the applied loads and the stress concentrations, using classical tools within the Linear Fracture Mechanics framework [69, 26, 48], or more sophisticated ones taking into account the generalized plasticity [17, 1, 25, 42, 54].

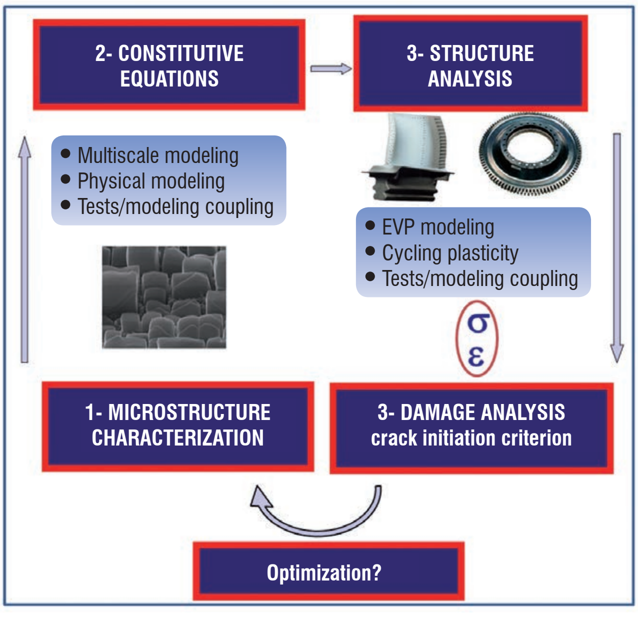


Figure 1 – Lifetime analysis workflow used as an optimization loop

In the near future, it will be possible to propose an optimization loop consisting in finding the best microstructures in the component, in order to delay the crack initiation and then improve the lifetime of the structure.

Generally, this dimensioning process for metallic structures involves at least the steps 2 to 4 which are the most critical and require the consistency cited above. The damage model must be adapted to the complexity of the performed calculation (elasticity, with reduced models, viscoplasticity taking into account strong non-linearities, only to mention growing complexities) or, conversely, the constitutive equations must be consistent with the fatigue damage model, depending on the availability of the models in the computational codes and/or the degree of sophistication of the analysis.

This consistency is the key to achieving correct results and reducing the scatter that is often observed.

In this paper, we focus our analysis on the more complex methods, based on calculations taking into account the non-linear behaviors linked to the cyclic hardening or softening of the material, the relaxation of the mean stress or the ratcheting, to name only the phenomena that are commonly observed. These computations of the material behavior are therefore associated with the fatigue damage models able to integrate all of this available information. Two fundamental issues are addressed: the loading multiaxiality and the temperature effects. However, this modeling step cannot be achieved without the development and validation of experimental tests. Again, the complexity of the test increases with the phenomena that we want to highlight, starting with "conventional" isothermal tests and achieving complex multiaxial anisothermal fatigue tests. The goal is to get closer to the operating conditions of the component, reproducing the temperature maps and the mechanical loads with regard to the geometrical stress concentrations in the best way possible.

The paper is divided into four sections. The first one is devoted to the presentation of constitutive equations developed at ONERA to model the non-linear behavior in cyclic elasto-viscoplasticity of metallic superalloys used in the hot parts of engine aircrafts. The second section presents an extensive literature review on fatigue damage models with respect to the position of our models. In the third section, particular emphasis is placed on the description of multiaxiality and mean stress effects, together with the development of sophisticated experimental tests. The last section of this paper presents some applications of this workflow analysis performed on increasingly complex structures, ranging from classical characterization tests up to real operating ones.

Cyclic inelastic analysis

The development of constitutive equations within the general thermodynamics framework of the continuum media and specifically in elasto-viscoplasticity is the core activity of the Metallic Materials and Structures Department at ONERA. This modeling stage is fundamental to properly reproduce the anisothermal viscoplastic cyclic behavior of the material, which can be complex regarding the several phenomena observed in service. For this purpose, thermo-mechanical tests have been developed, together with the modeling approach, allowing to observe and to characterize the dissipative mechanisms, in order to identify the material parameters of the constitutive equations and, finally, to validate these models on structural specimens representative of aeroengine parts in terms of stress/strain fields.

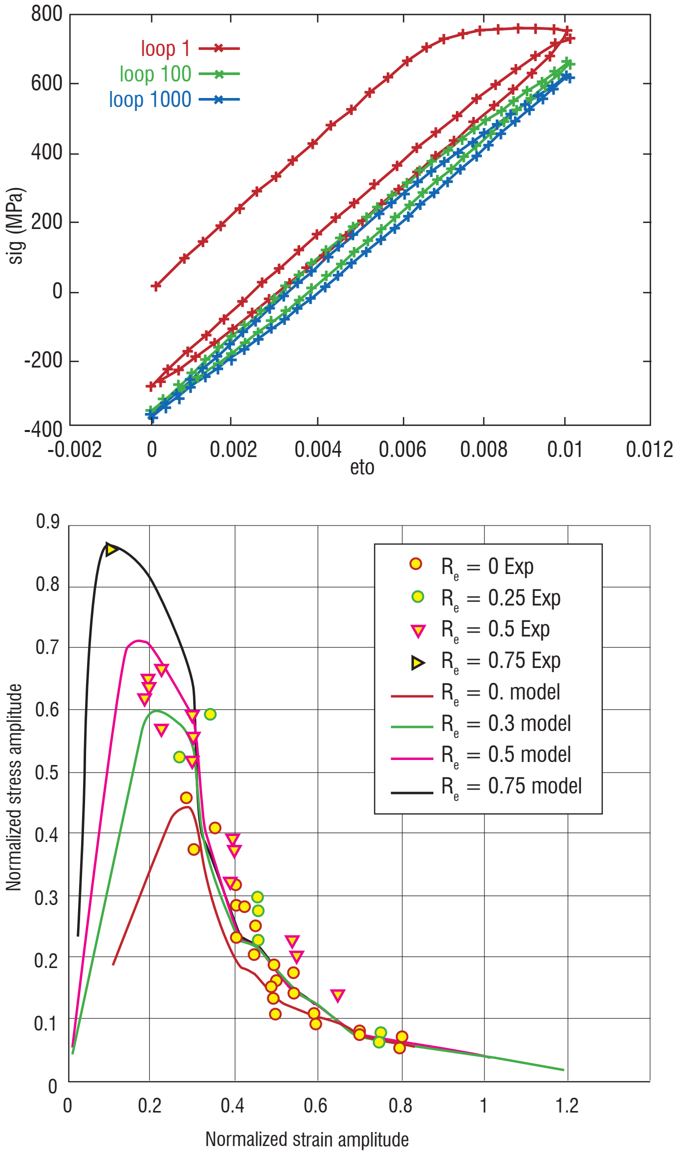
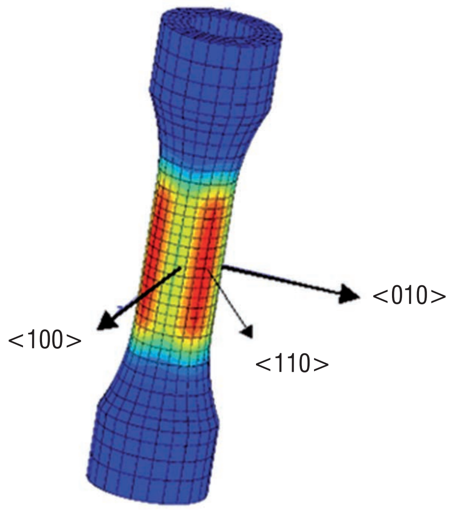


Figure 2 – Ti64, cyclic softening (up) and mean stress relaxation (down)

The observation of experimental results of the Ti64 superalloy cyclic behavior in figure 2 shows a cyclic softening when the material is loaded under constrained strain. Also, for a strain ratio ($\varepsilon_{min}/\varepsilon_{max}$) equal to 0 and a strain amplitude lower than 1%, the mean stress does not relax to 0 as presented in figure 2 (right). It is therefore essential that the constitutive equations representative of the material behavior take into account these phenomena, in order to correctly predict the stress and strain fields at the stabilized state in the structural component, i.e., their levels and also their amplitudes. For this purpose, the formalism adopted to correctly represent the cyclic behavior of metallic materials is characterized by:

- A criterion for the flow rule based on the octahedral shear stress invariant,
- Non-linear isotropic hardenings (to describe the cyclic softening or hardening),
- Non-linear kinematic hardenings (to describe the Bauschinger effect), or more complex relations, in order to reproduce the partial relaxation of the mean stress for dissymmetric strain loading conditions, as observed experimentally (see figure 2) [10].
- This characterization being performed for high temperatures, the viscosity of the material is described by a Norton law, or more recently by a hyperbolic sine law, in order to be able to simulate the behavior in a wider range of strain rates, namely a saturation of the strain rate effects for high plastic strain rates.

These constitutive equations are the basis of the model for isotropic materials. Based on the same formalism but performed at the scale of the grain, a crystal plasticity model has been proposed by [56] and recently improved at ONERA by the introduction of a recovery term in the back stress, to allow a better description of the secondary creep in metals. In this model, internal variables related to the isotropic and kinematic hardenings are introduced on each crystallographic slip plane. The model takes the anisotropic behavior of metallic materials implicitly into account and it has been successfully applied to model the non-linear behavior of a f.c.c. Ni-based single crystal superalloy. In [5] authors investigated torsion tests of a single crystal superalloy at 950°C. These tests were performed under torque control and show the structural effect due to the crystal viscoplasticity (figure 3). This peculiar case requires Finite Element calculations, due to the appearance of zones with higher strains depending on the material secondary direction and obviously to the complex redistribution of stresses. This work highlighted the importance and the impact of crystal anisotropy (octahedral and cubic slip systems) on mechanical behavior.



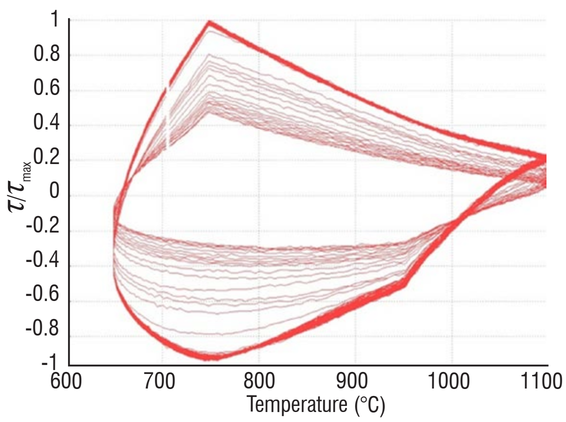


Figure 3 – Torsional fatigue at 950°C of a single crystal superalloy

This work has been recently improved by [33] and [39], who have investigated the influence of the evolution of the microstructure on the mechanical properties of this single crystal superalloy. When the material is subjected to creep at high temperatures, its microstructure evolves and precipitates lose their initially cuboidal shape to reach a rafted pattern. This rafting process has a strong influence on the macroscopic behavior. Some additional internal variables have been introduced in the constitutive equations, in order to describe the evolution of the shape of the precipitates as a function of the load history and its impact on the material parameters. The result of this analysis is shown in figure 4, which presents a comparison between cyclic tests performed on both the reference material and the modified microstructure. In this figure it is possible to see the influence of the rafted microstructure on the overall behavior, inducing a softer macroscopic response that is qualitatively well represented by the proposed model. Work is in progress to improve the results of the modeling.

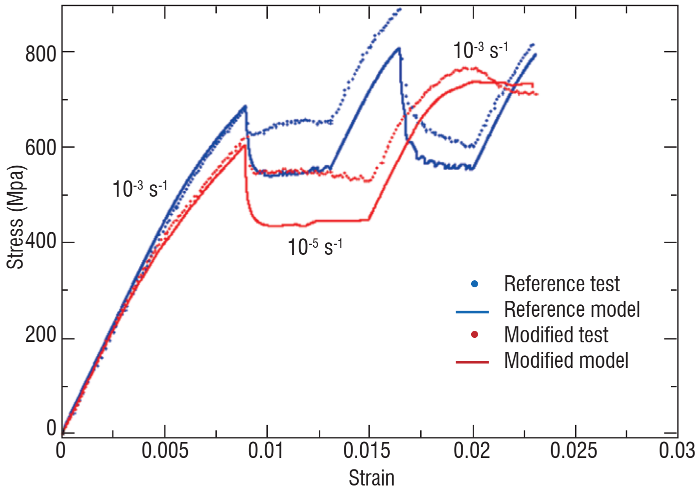


Figure 4 – Tension tests and simulations at two different strain rates, taking into account ageing effects

A similar approach has been proposed for a polycrystalline Nickel based superalloy, N18, [4]. A precipitation model [68] was improved to predict the evolution of the size and the volume fraction of γ' secondary and tertiary precipitates as a function of the thermal history. The influence of the precipitate distribution on the mechanical response of the material is then introduced in the plastic threshold of the viscoplastic model. More specifically, Boittin [4] used, to account for the precipitate distribution, relations based on approaches considering the resolved shear stress necessary to move a dislocation through a glide plane containing precipitates as Orowan: for dislocations bypassing the precipitates, or Hüther and Reppich [41]: for strongly coupled dislocations shearing the precipitates or Brown and Ham [6]: for weakly coupled dislocations shearing the precipitates. The proposed model provided a good description of the cyclic behavior of several different γ' particle distributions obtained through various cooling paths and/or aging treatments in coarse grain size superalloy N18, as shown in figure 5.

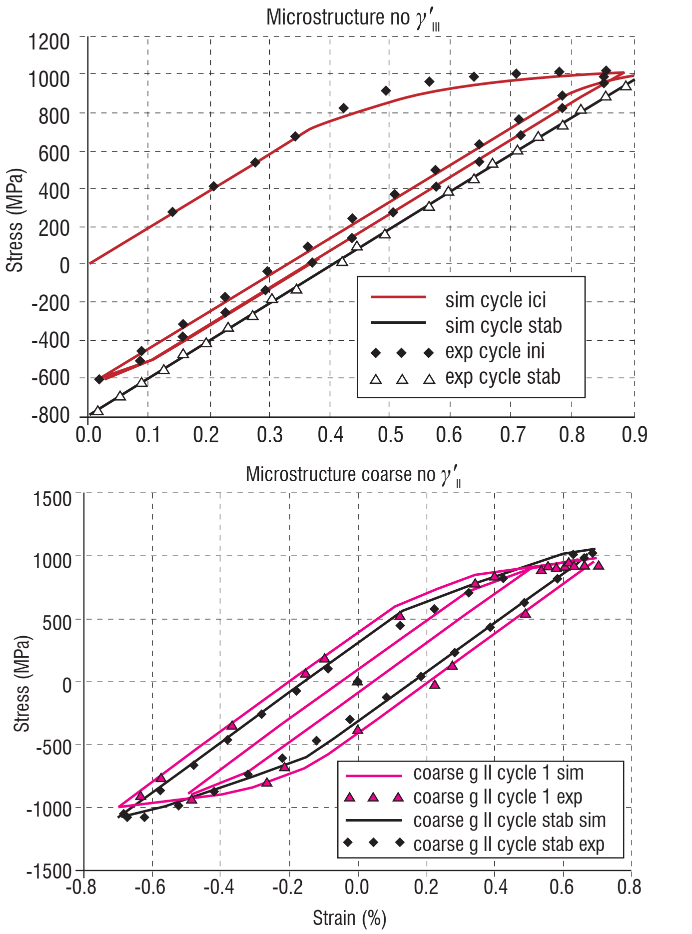


Figure 5 – Influence of the precipitate distribution on the cyclic behavior of coarse grain size superalloy N18 - Comparison of the model and the experimental response in the first and stabilized cycle

On the other hand, experimental observations have shown that Nickel-based or Cobalt-based superalloys could present very complex viscoplastic behavior, depending on the applied temperature and related to the dynamic strain aging phenomena [12]. In an intermediate temperature range (from 300°C to 800°C), a very important hardening process that depends on the applied plastic strain can be observed in the material. Other crucial phenomena are the inverse strain rate dependency and serrations occurring in the strain-stress curve induced by the propagation in the material of strain rate localization bands. Other effects can also be observed, like static recovery of kinematic hardening, even at temperatures around 600°C. The classical macroscopic formalism presented before has been enriched to account for these phenomena and to allow an accurate description of the observed experimental behavior.

Figure 6 summarizes the possibilities of the viscoplastic constitutive equations, including cycling hardening and dynamic strain aging, to accurately estimate the material behavior under complex thermo-mechanical cyclic loads. As can be observed, the model prediction (solid black line) is very close to the experimental data (red points).

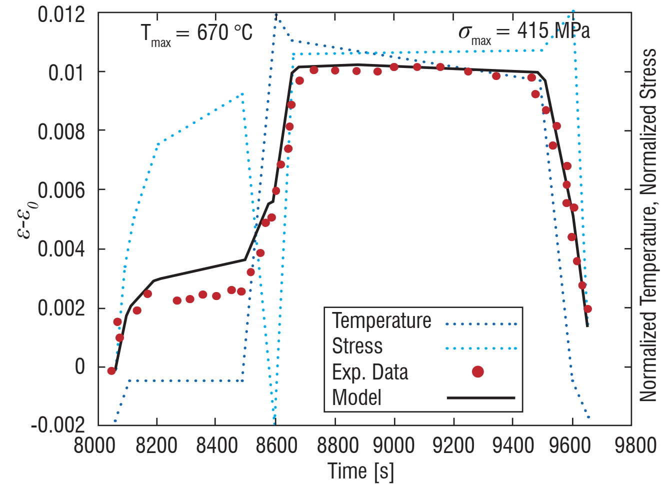


Figure 6 – Anisothermal cyclic behavior identification of a cobalt based superalloy

Another important step of this analysis (as proposed previously) is the validation of the model under anisothermal conditions. Once the model parameters are identified from a set of isothermal characterization tests, it is validated on cyclic thermo-mechanical tension/compression tests with in-phase or out-of-phase load paths interacting time/strain /temperature, as presented in figure 7 for the load path and figure 8 for the comparison between experimental results and the model, in the case of the AM1 single crystal superalloy. A more complex validation case concerns tension/torsion Thermo-Mechanical Fatigue, as represented in figure 9. It is worth noting that the main difficulty of these TMF tests is the application of the mechanical strain obtained by the control of the total strain during the thermal cycle. The structural effect in torsion requested to develop a specific algorithm to control the imposed displacement of the crosshead using Finite Elements simulations. This numerical scheme is based on a perturbation method, in order to impose the proper displacement to obtain locally the desired strain measured by the extensometer.

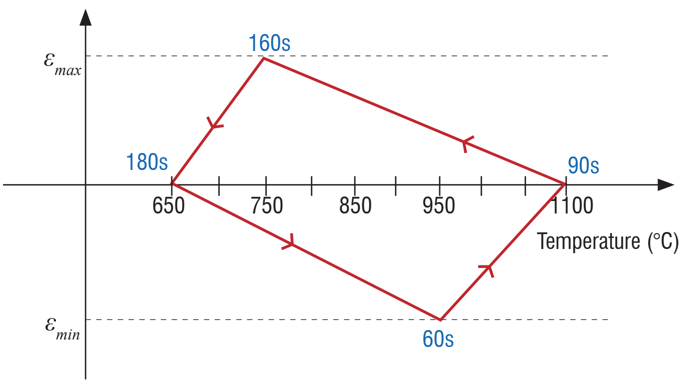


Figure 7 – Thermo-mechanical applied load on cylindrical specimens

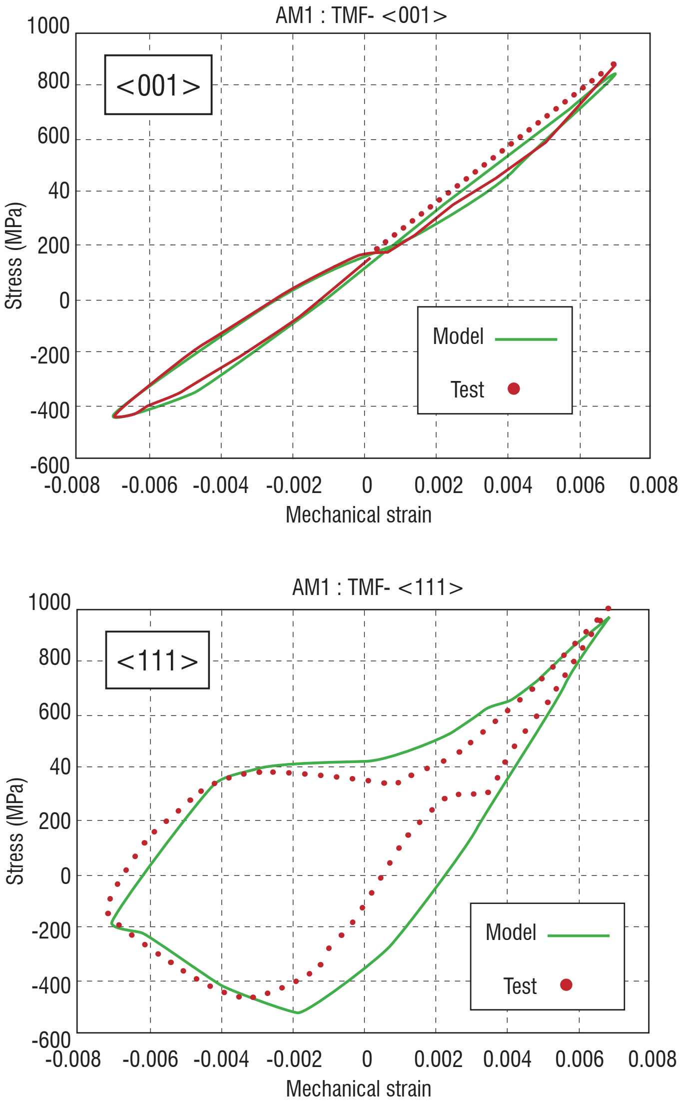


Figure 8 – Stress/mechanical strain behavior in two directions of the single crystal superalloy AM1

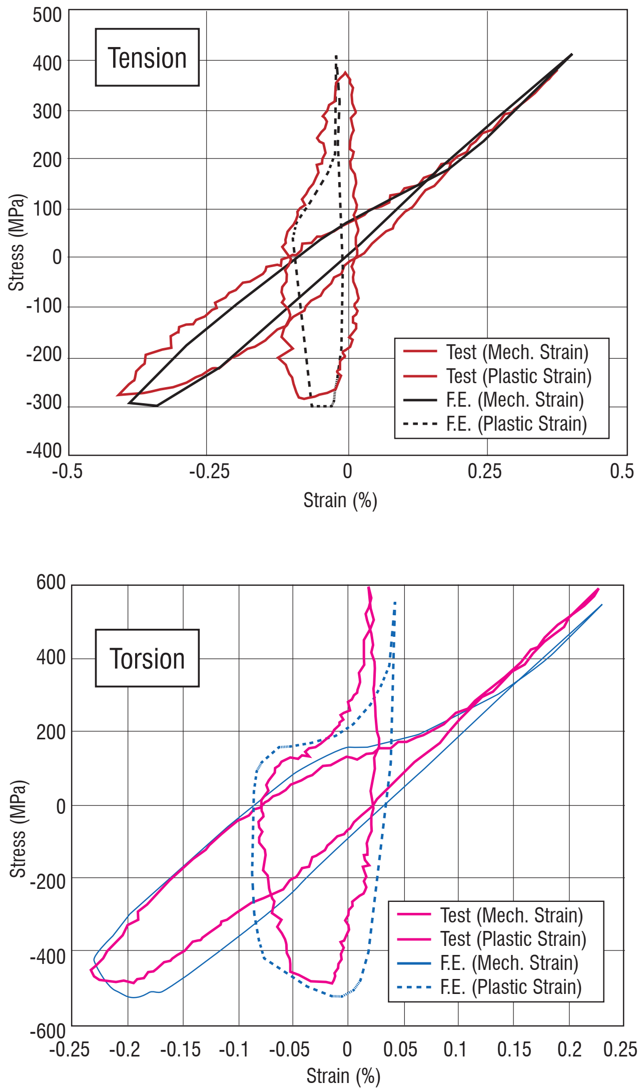


Figure 9 – Stabilized mechanical stress-strain behavior of <001>-oriented single crystal superalloy AM1 under axial-torsional Thermo-Mechanical Fatigue (TMF cycle defined in figure 7)

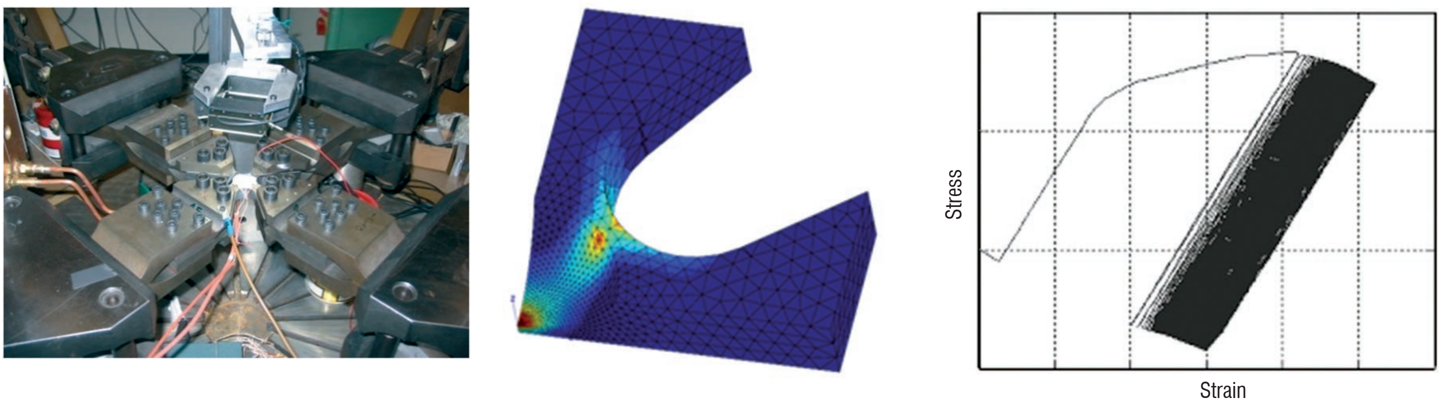


Figure 10 – Biaxial tensile tests device (left) and the finite element simulation (cumulative plastic strain (middle)) on a nickel based specimen up until the stabilized stress/strain state (right)

Finally, once the model has been identified and validated, it is used in the finite element analysis of the structure, as presented in figure 10 (left), for the simulation of the cyclic behavior of a cruciform specimen, on which it is possible to impose multiaxial (tension/tension) loads.

Figure 10 (right) presents the contours of the cumulative plastic strain stress obtained for an equibiaxial tension finite element simulation and the cyclic response on a point in the critical region (the center of the specimen), showing that the stabilized cycle is reached after more than 100 cycles. This important evolution of the stresses and strains is a key point for the fatigue damage analysis.

Multiaxial and anisothermal fatigue modeling

Critical aeroengine components, such as cooled turbine blades, turbine and compressor discs or combustion chambers, are submitted to complex thermo- mechanical loadings that can induce multiaxial stress states. The interaction between low cycle fatigue and high cycle fatigue, combined with high biaxialities and mean stresses, is one of the main topics of concern in fatigue. The exposure to high temperatures will additionally induce various mechanisms, such as creep and oxidation. For turbine discs, the microstructure of the constitutive material and the equibiaxial state play a significant role, while for turbine blades, high service temperatures involve a more important influence of creep and oxidation interacting with geometrical singularity effects induced by the cooling channels.

Also, it is important to specify that, despite the variety of the approaches, the fatigue damage remains closely linked to the effects of the material microstructure in connection with the applied mechanical load, for instance, the multiaxial state and the level of an equivalent mean stress. This is a major difficulty for correctly modeling the fatigue behavior taking into account this multiaxiality, the influence of time and temperature dependent phenomena, and the mean stress effects in a very complex geometry.

Multiaxial models

As has already been mentioned in the introduction, many multiaxial criteria can be found in the literature. From Garud's paper [32], a trend has emerged to classify the models according to several categories:

The empirical models, mainly based on experimental observations, are the oldest ones and began to be developed in the late nineteenth century with the rise of railways. These multiaxial criteria, often based on bending-torsion tests, offer endurance curves (ellipse quadrant). This category includes the work of [37, 63, 64] and extensions of the Manson-Coffin model for low cycle fatigue, taking into account the influence of plasticity.

The next category concerns criteria based on critical plane approaches, which have received great attention in the literature. These criteria were developed from experimental observations showing that, in fatigue, the crack initiates in a critical crystallographic plane and then propagates perpendicular to the direction of the maximum principal stress. The various proposed formulae are different, but the process to follow is merely the same. Firstly, one must find the critical plane and secondly check whether the criterion is met on this plane. It is possible to classify these approaches as stress-based, generally developed for HCF [29, 51, 52, 24, 53, 21, 14, 67, 9], strain-based, which are also valid in LCF ([7, 45] and its variants, the criterion of [28]) and energy-based, discussed hereafter.

Energy-based approaches use the product of the stress and strain to quantify the fatigue damage. Various energy parameters are available and can be divided into three groups, depending on the strain energy density per cycle chosen as a damage parameter: criteria based on elastic strain energy density [65], valid for high cycle fatigue, criteria based on plastic strain energy density, [59, 32] valid for low cycle fatigue and finally criteria based on elastoplastic strain density energy [27, 70] with the aim of covering both high and low cycle fatigue. The most recent works on multiaxial fatigue proposed models based on critical plane approaches using an energy damage parameter, such as the criterion of Liu [49, 50], which describes the crack initiation in three modes, one in the normal direction and two modes in the plane perpendicular to the normal direction (see also [18, 34, 35]). One can also mention the well-known SWT model [74], which uses the product of the maximum normal stress by the strain amplitude in a chosen critical plane for multiaxial applications.

The last more popular category concerns equivalent effective stress or strain models. Based on the invariants of the mechanical fields, such models are essentially extensions of static yield criteria and often combine the hydrostatic pressure to take into account the mean-stress effects and the octahedral shear stress amplitude. This framework includes the models proposed by Sines [73] and Crossland [19] (which generalizes [38]). Chaudonneret [15, 16] proposed in 1993 a multiaxial extension of the ONERA fatigue damage model [13], which has the particularity of describing, in accordance with experimental observations, non-linear damage accumulation for complex variable amplitude loadings. This model was based on a compilation of many two-level fatigue test results and has the capability of reproducing sequence effects and more complicated loading sequences. In particular, it is able to take into account the damage effects of loading cycles performed below the initial fatigue limit. A new formulation is thus proposed to describe multiaxial loadings, providing a better overall adjustment through a new material parameter that allows, for specific values, to obtain Sines, Crossland or results close to the Dang-Van criterion. Using [71], the influence of the hydrostatic pressure was also introduced for the static fracture. In addition, to account for non-proportional loadings, she introduced the concept of stress path and defined a weighted octahedral shear amplitude.

Such a general formalism has served to develop life assessment tools for high temperature applications by coupling the fatigue damage with other damaging mechanisms, such as creep [72, 57, 70, 23] or oxidation [62, 61, 2].

The ONERA creep-fatigue damage model has been applied with success on several materials in various applications (gas turbine blade polycrystalline superalloys, turbine disc materials and waspaloy during the initial design of some components of the Vulcain engine of Ariane V). For complex thermo-mechanical loadings, a multiaxial extension based on the multisurface plasticity theory [60] of the commonly uniaxial rainflow technique has been proposed, together with a calculation of an equivalent temperature, as proposed by Taira [75] over the thermo-mechanical cycle using a simplified incremental model. However, for high temperature applications, as for turbine blade applications, Gallerneau [31] shows insufficiencies of the creep-fatigue damage model, namely due to oxidation effects. A new formulation is then proposed, based on the separation between microinitiation and micropropagation stages and incorporating environment enhanced damage effects into the framework of a creep-fatigue-oxidation model. He also proposed an extension of the Hayhurst criterion [40] to describe multiaxial creep loadings, in order to account for the anisotropy in creep resistance of single crystal superalloys.

Despite several other formulations having been proposed in the literature to describe the interaction between fatigue, creep and eventually oxidation damages, few authors [43, 55, 57, 2, 70, 77, 20, 3] address the case of anisothermal multiaxial loadings.

Figure 11 shows the ability of Gallerneau's model to correctly predict lifetimes for different anisothermal conditions. The material considered is again AM1 single crystal superalloy. The critical cycling mentioned in this figure is relative to the anisothermal load path presented in figure 7, while other cycling is more relative to proportional loadings. Another feature is the accurate description of torsional loading under isothermal and anisothermal conditions, taking into account crystal plasticity and isotropic damage.

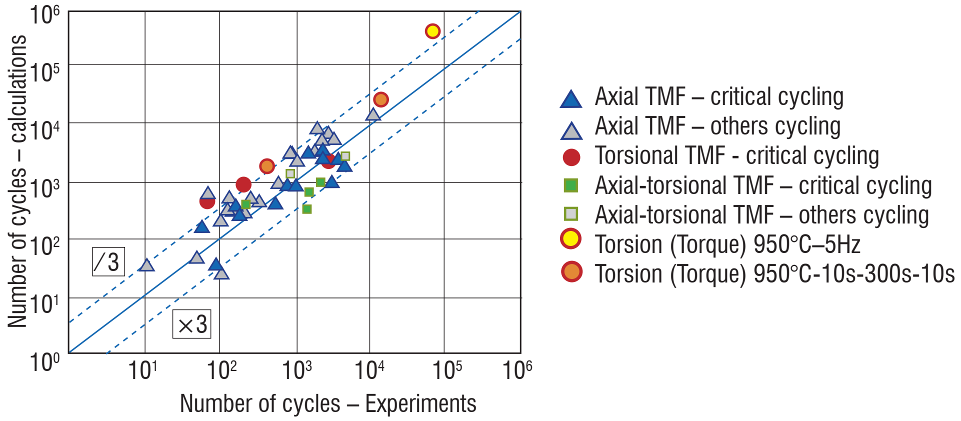


Figure 11 – Lifetime predictions for several anisothermal and multiaxial tests

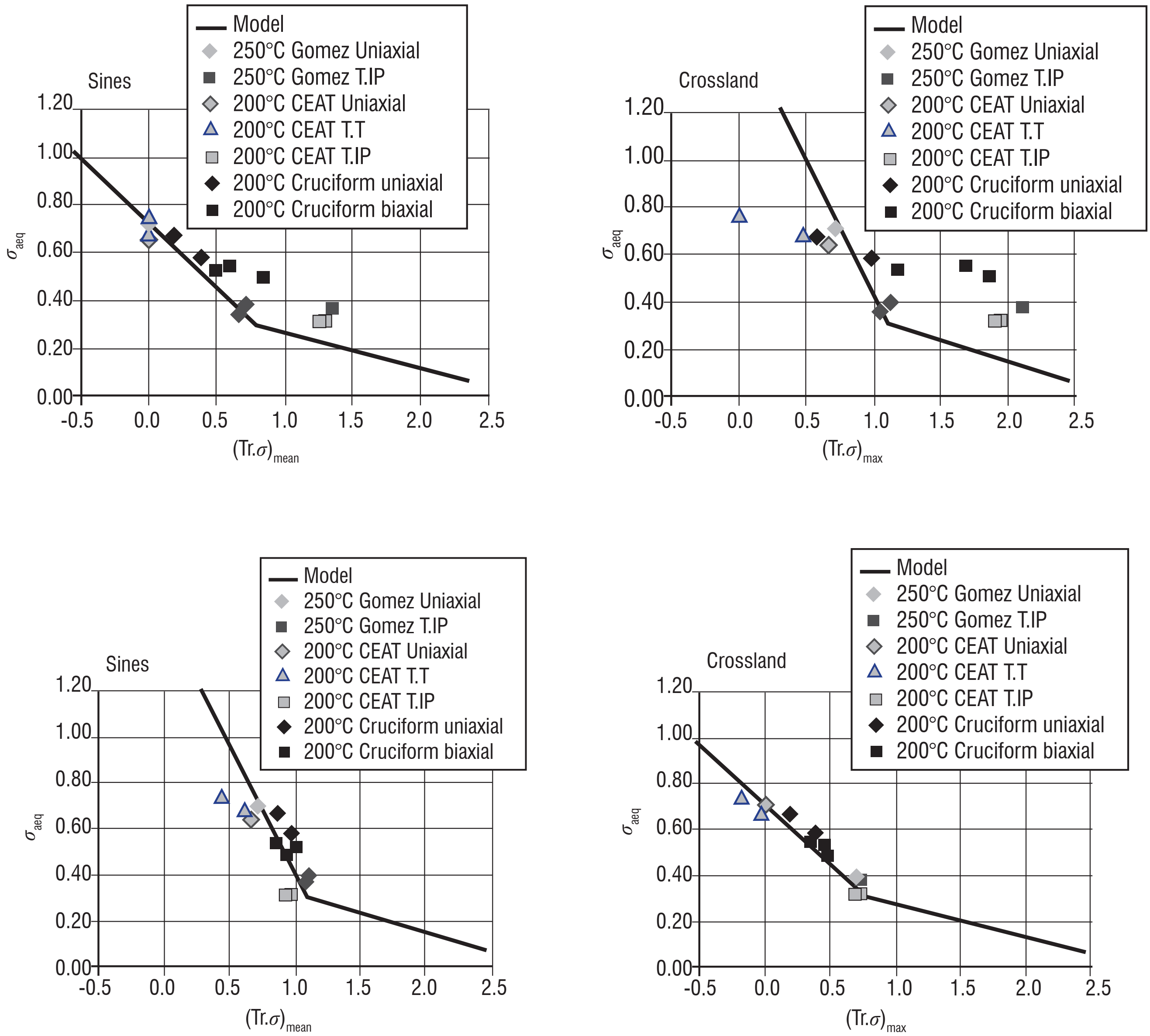


Figure 12 – Comparison of Sines, Crossland, Gonçalves and the ONERA criteria on Ti64 superalloy

A new multiaxial criterion

The majority of the aforementioned models often failed to accurately predict the lifetime for complex loads involving an important contribution of the mean stress and multiaxiality. Recently Bonnand [5] proposed a new multiaxial formulation for low temperature fatigue that can correctly reproduce experimental results obtained in tests involving both high multiaxiality and significant mean stress effects. This model has been formulated with the objective of accurately estimating the shear and equibiaxial conditions. The effective stress is written as

$$\sigma_{a_{eff}} = \sigma_{a_{eq}} \left(1 + b\,\sigma_{D_0} t_{eq}\right) \quad (1)$$

with the following expression for the triaxiality factor:

$$t_{eq} = \xi \frac{s_F\, t_F}{1+\left|t_F\right|} + (1-\xi)\left(s_F - 1\right) \quad (2)$$

where $t_F = \dfrac{\left(Tr\sigma\right)_{mean}}{\sigma_{a_{eq}}}$ and $s_F - 1 = \dfrac{\sigma_{p\max} - \sigma_{a_{eq}}}{\sigma_{a_{eq}}}$, $\sigma_{a_{eq}}$ is the octahedral shear stress amplitude, $\left(Tr\sigma\right)_{mean}$ is the mean value of the first stress invariant during the cycle and finally $\sigma_{p_{\max}}$ is the maximum stress Eigen. The term σ_{D0} represents the fatigue limit for a reversed cycle at 10^7 cycles and b is a material parameter that will be identified from uniaxial tests with mean stress effects. Finally ξ is a material parameter. This new model gives results similar to the Sines one when t_F tends towards zero and similar to a model with $t_{eq} = s_F$ for high values of t_F.

This new formalism has been compared with models in the literature ([73, 19, 36] for instance) and give very accurate results, as presented in figure 11 (from [5]), which can be seen as a multiaxial extension of Haigh's diagram.

Lifetime analysis of critical components

In order to validate or disprove the existing models and to propose a new formalism, a wide experimental campaign was conducted on aeronautical superalloys, such as Ti64 and INCO718 for discs or the AM1superalloy developed for turbine blades, on a set of test specimens ranging from a classical geometry used for characterization, up to technological specimens approximating real geometries.

The laboratory of complex tests at ONERA has several experimental devices dedicated to multiaxial and anisothermal fatigue tests. Each device has its own specificity to enrich the experimental database, especially in poorly explored areas (loads, geometries,, etc.). It is possible to perform uniaxial characterization tests, as well as biaxial tests under tension/torsion or tension/internal pressure on tubular specimens, with in-phase or out-of-phase temperature evolutions and biaxial tests (tension/tension) on cruciform specimens for various applied loads ratios. For all of these tests, the temperature is imposed by induction, which, regarding its compactness, enables mechanical and optical measurements to be performed to instrument the test as well as possible.

To illustrate these developments and the complexity of experimental tests and modeling performed within this framework, the developments around the fatigue analysis of the single crystal superalloy AM1 are presented hereafter. This application example is part of recent PhD work [22].

The purpose of the study was to investigate the lifetime of single crystal high pressure turbine blades. The geometry of these blades is very complex, with areas involving cooling channels inducing significant mechanical and thermal gradients, which are essential to evaluate. For this purpose, two geometries were tested: the smooth cylindrical specimen heated outside and cooled inside by forced air circulation and the same cylindrical specimen but with a network of cooling holes. These specimens are loaded with the real thermal gradients observed in operating blades. The geometry of the perforated specimen is shown in figure 13 (the perforated area is magnified), together with the high temperature experimental device (from [46]).

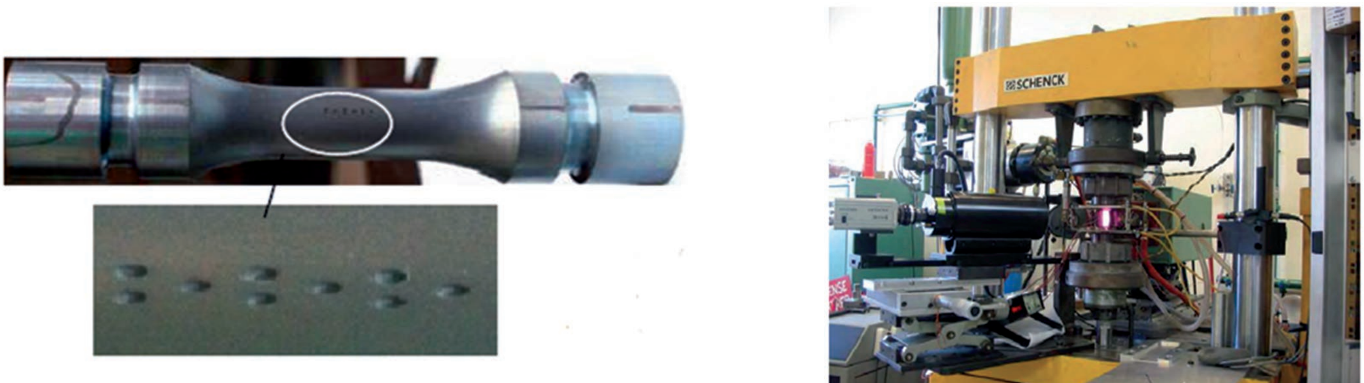


Figure 13 – Perforated tubular specimen (left) and the high temperature tension/torsion/internal pressure experimental device (right)

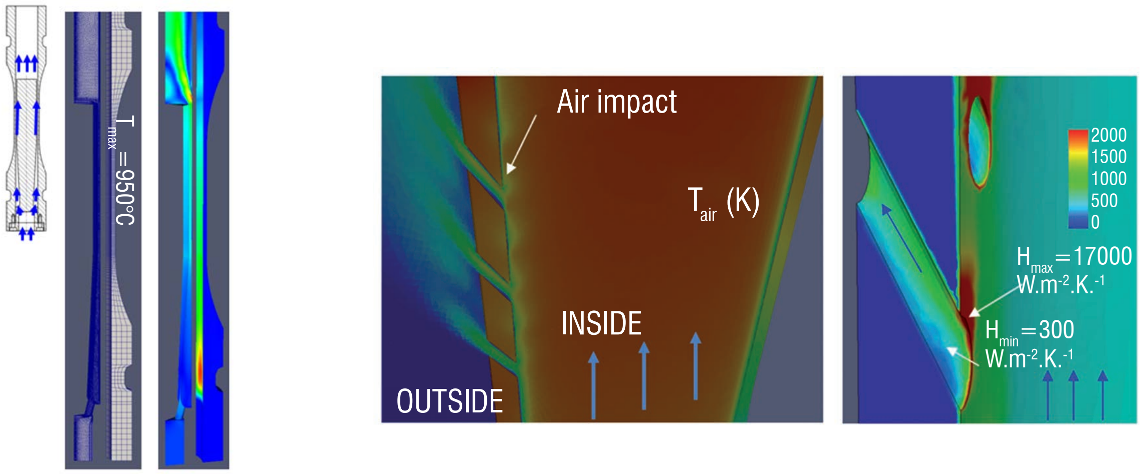


Figure 14 – Thermal/Solid/Fluid coupled calculation: smooth specimen (left) and perforated specimen (right). Temperature contours and the convective heat transfer coefficient h governed by the fluid velocity

This progressive approach validated the experimental device and the associated measures developed to properly assess the thermo-mechanical fields (temperature gradient and strain gradient). In addition, an analysis of such complexity cannot be derived only from experimental results, it is also necessary to perform a numerical analysis in order to adequately catch fields that are not measurable, such as the temperature inside the cooling channels. For this purpose, fully coupled calculations in Thermal/Solid/Fluid mechanics (Zset and Cedre codes from ONERA) have been carried out on these complex geometries. The thermal gradient over the specimen wall was estimated at 68°C for a 1mm thickness. Complex thermo-mechanical cycles were applied to simulate a real engine mission, as presented in figure 14. Heating and cooling rates were up to 50°C/s with a good reproducibility and stability over lots of cycles. In this configuration, copper coils make it possible to avoid the use of classical extensometers with fixed gage length. This is the reason why Digital Image Correlation (DIC) was extended to the high temperature range by treating the loss of optical contrast due to Planck's law. This image methodology allows "strains" to be measured by means of a virtual extensometer, which is used together with finite element calculations. Under these conditions, the proposed strain must be considered as a relative displacement integrating the temperature inhomogeneity into the gage length. The fatigue life prediction is performed as a post calculation, using the fatigue-creep interaction damage model presented previously.

Another main difficulty arising during the fatigue damage analysis of a structure or a specimen containing holes is linked to the gradient effect. It has been well established that the crack will initiate faster for low stress concentration gradients than for higher ones for the same maximum local stress. This is related to the volume of matter affected by the gradient and the potential defects present in this volume. A specific procedure has been developed [46] in order to take into account this fact, consisting in proposing a non-local damage approach, averaging the damage parameter, or the variables that govern the damage, over a spherical volume. The radius of this sphere is a new parameter of the model.

Figure 14 is an illustration of this application on the tubular specimen using the anisothermal fatigue damage model proposed by [31]. Two sets of tests and their simulations are presented: isothermal fatigue (TF) (with a steady state temperature gradient) and thermo-mechanical fatigue (TMF) performed on smooth specimens and perforated ones subjected to relatively complex cyclic loads.

The comparison between experimental results and life prediction is quite satisfactory. The slight over-estimation observed on smooth specimens was shown by DIC to result from the ratcheting effect not precisely described during the hold time. It is important to notice that this agreement has only been possible by taking into account in the modeling the true thermal gradient in the thickness of the tubular specimen and around the holes, the stress gradient and the size effect close to the holes, the multiaxiality and the mean stress effects in the specimen.

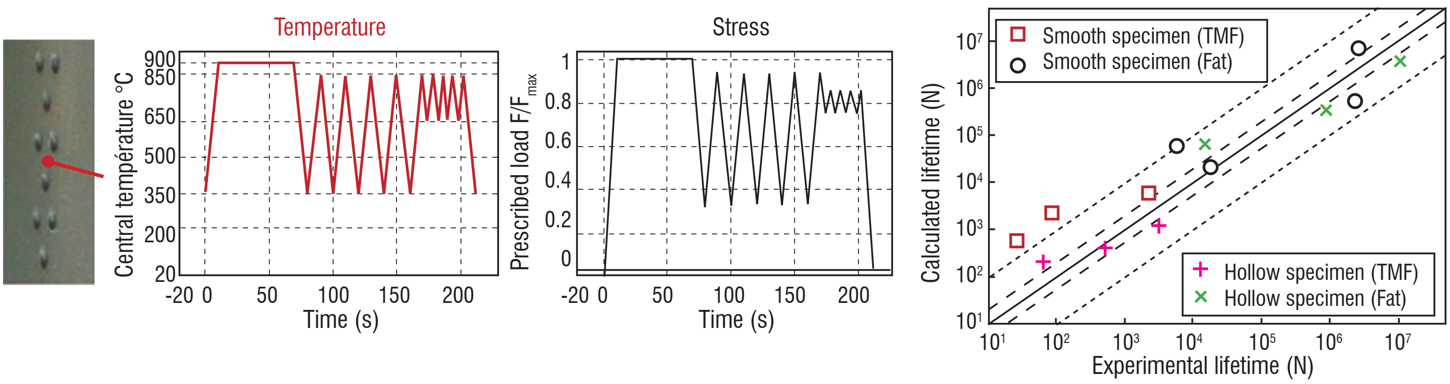


Figure 15 – Lifetime predictions for complex geometries combined with complex cyclic loads

Conclusion and perspectives

The purpose of this paper was to make an assessment of the fatigue damage modeling taking into account the effects induced by the temperature and multiaxial loadings. It showed the strong influence induced by a non-zero mean stress on the lifetimes observed in experimental results obtained on standard specimens, as well as on technological ones representative of real structures. The main findings can be summarized as follows:

It is necessary to develop consistent approaches in the lifetime analysis workflow, which includes the three main stages from the material experimental characterization (microstructure, behavior, fatigue,, etc.) and the development of constitutive equations, up to the fatigue damage model.

While it is possible, for the modeling of the constitutive equations, to define a general framework based on a given approach that will be enhanced according to the phenomena taken into account and the degree of sophistication that we want to introduce, this kind of framework does not exist for fatigue damage modeling and requires the approach to be adapted according to the observed experimental results. For example, for a given material, a strain invariant based approach will be sufficient, whereas for another material (or for the same one under different conditions), an energy-based or critical-plan approach will be more appropriate. This is induced particularly by the physical phenomena involved in the analysis, which are not only numerous but also very distinct and directly linked to the material microstructure, its defects and the stress/strain states. It is therefore necessary to distinguish the modeling of the microstructure for the constitutive equations from the modeling of the microstructure for the fatigue damage models, since the physical phenomena do not develop necessarily at the same scales.

In the case of severe thermo-mechanical loads, as in the example of the cooled blade, it is necessary to reproduce the applied loads as precisely as possible from the experimental point of view, as well as from the numerical point of view. In the latter case, multi-physics coupled approaches must be developed to approximate the real in-service conditions and to be able to expect predictive results to be produced.

These points define the main research topics that we will follow over the next decade ■

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