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Incremental lifing method applied to high temperature aeronautical component

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Abstract — This study aims to determine the life time of turbo-machines combustion chambers manufactured in superalloy or turbine blades made of single crystal material. The determination of crack initiation spots in fatigue is based on an incremental damage law applied on finite element calculations. Incremental damage laws present many advantages: it avoids any concept of cycle counting and it is more suitable for calculation with complex cycles. This numerical damage model is implemented as a post processor. First, the stored energy is computed via the accumulation of plastic strain. Then, the stored energy eventually reaches a threshold from which damage starts to grow. Finally, the cumulated damage reaches a critical value corresponding to crack initiation. Various forms of energy accumulation and energy threshold are presented. In particular, a decoupled calculation of stored energy using internal variables of the Chaboche behavior is detailed. Two plastic potentials allow taking into account low and fast strain rate viscosities. In this scheme, different methods of energy accumulation are used for creep and fatigue contributions. The reliability is then tested on high temperature experimental results, representative of classic chamber or turbine blade loads. Finally, the robustness is evaluated on low temperature test results. The good correlation between numerical and experimental Wöhler curves validates the incremental life-time prediction with a decoupled method. Further numerical simulations will validate its industrial use.

Key-words — lifing method, high temperature behavior, turbine blade, combustion chamber

1. Introduction

The drastic safety standards imposed in aeronautics imply a good knowledge of the damage mechanisms of engines parts. In order to predict correctly their life time during complex cycles, the “cycle vision” of fatigue has reached its limits.

The object of this study is to fit a new incremental model of life prediction. This model will be used to describe complex loads applied on the combustion chambers or high pressure turbine blades of Snecma engines. The materials considered here are Ha188 for combustion chambers and single crystal AM1 for high pressure turbine blades.

Combustion chambers and high pressure turbine blades are parts with complex geometry, subjected to rough variations, in time, amplitude and of temperature. These solicitations lead to strong mechanical anisotropic loads. It is then advisable to adopt an efficient model compatible with these extreme conditions. The part being subjected to high temperatures (between 600°C and 1000°C for chambers), the fatigue comes along inevitably with creep as for the initiation and the growth of the damage.

Regarding the temperature seen by parts like combustion chambers and high pressure turbine blades, a viscoplastic behavior has to be considered in order to determine the stress and strain seen by these

parts during flight. A two potential model has been used: The first one for the modeling of cyclic loads and the second one for the modeling of creep, stress relaxation and also mean stress relaxation.

The life of a part undergoing cyclic loads decomposes into two main steps. The time before initiation of the damage characterizes the first phase where the material deforms plastically without appearance of microscopic cracks. After the initiation, begin the second phase, with the seeding and the distribution of porosities and/or cracks in the material until break. It is interesting to note that the first domain stands for more than 90 % of the life expectancy of a part. So, in a concern of simplicity, it is possible to realize a model that calculates the time before initiation T_d , defined as the moment of appearance of porosities or cracks at the microscopic scale. Then, we can be interested in improving the precision of the prediction, with a damage model that describes the initiation time T_r ($T_r = T_d + T_e$) characterized by the presence of a macroscopic crack. Then the remaining time before breaking can be computed by using a crack growth model. The total life expectancy would be the sum of the three durations.

2. Two potential behavior Chaboche model

Two materials are considered in this paper. Haynes 188 (Ha188) which is a cobalt base superalloy used in the combustion chambers for its high ductility and very good resistance regarding oxidation and corrosion. The other one is AM1 which is a single crystal nickel base superalloy used for high pressure turbine blades. It is highly resistant to creep loads and also to oxidation.

In terms of behavior modeling, these two materials are very different. Ha188 exhibits strain ageing effects between 650°C and 800°C and also cyclic hardening [1],[2]. So only the temperature of 900°C will be treated in this article for Ha188. AM1 is a single crystal material, so its behavior is anisotropic. We will only consider an isotropic behavior for AM1 based on the behavior of the <001> direction. Whereas other authors have developed more advanced model [3]

The two potential model is explained hereafter. It is based on the framework developed by Chaboche [4], [5].

Isotropic linear elasticity

Linear elasticity connects stress and strain by the Hook relationship:

$$\sigma_{ij} = \frac{E}{1+\nu} \varepsilon_{ij} + \frac{\nu E}{(1+\nu)(1-2\nu)} \varepsilon_{kk} \delta_{ij} \quad (1)$$

where E and ν are respectively Young modulus and Poisson ration.

Plasticity criterion

The elastic domain is characterized by the reversible nature of the deformations. On the contrary, beyond a certain level of stress, appear inelastic deformations. In order to take into account the independence of plasticity to hydrostatic pressure as well as the multiaxial threshold of plasticity of numerous metals, the criterion of von Mises has been used:

$$f = J_2(s - X) - R = 0 \quad (2)$$

where $J_2(s-X)$ is the equivalent von Mises stress and R is the effective stress corresponding to the yield stress.

The equivalent von Mises Stress is written as follow in the tensorial stress space:

$$J_2(\sigma) = \sqrt{\frac{3}{2} s : s} = \sqrt{\frac{1}{2} [(\sigma_{11} - \sigma_{22})^2 + (\sigma_{22} - \sigma_{33})^2 + (\sigma_{33} - \sigma_{11})^2 + 6(\sigma_{12}^2 + \sigma_{23}^2 + \sigma_{13}^2)]^{1/2}} \quad (3)$$

where s is the stress deviator computed as $s = \sigma - \frac{1}{3}Tr(\sigma)I$.

Isotropic hardening

The two materials considered in this study shows cyclic softening or/and cyclic hardening. Nevertheless, the power of actual computers is not sufficient to compute many cycles in order to get the stabilized stress state. The hypothesis considered in this work is that the identification of the behavior is made on stabilized cycle. So we get $R=R_0$.

Kinematic hardening

As the parts considered here will see cyclic loads (one cycle is one flight), we have to take into account the Bauschinger effect which is well represented by the Armstrong Frederick law:

$$dX = \frac{2}{3}Cd\varepsilon^p - DXdp \quad (4)$$

where C and D are 2 material parameters describing the evolution of the kinematic part of stress. With p the accumulated plastic strain defined by the relationship:

$$p_i = \int_0^i \sqrt{\frac{3}{2} \dot{\varepsilon}_i^p : \dot{\varepsilon}_i^p} d\tau \quad (5)$$

and i the potential (slow or fast).

Viscoplasticity

Components considered in this work are used at high temperature. One has to manage the time dependence of stress, and so, add viscosity into the model. The retained formulation is the Norton one:

$$\dot{p} = \left\langle \frac{f}{K} \right\rangle^n \quad (6)$$

Where $\langle a \rangle$ is equal to a if $a > 0$ else 0. This expression has two parameters K and n .

The plasticity criterion f is given by equation (7). This function can be positive in the case of viscoplasticity whereas it has to be equal to zero in case of time independent plasticity.

$$f = J_2(\sigma - X) - R_0 \quad (7)$$

As the temperatures seen by the parts we consider are high enough to show creep, we have to include in the model another ingredient to represent it. With a Norton viscosity we are only able to take into account the strain rate effect (typically $\dot{\varepsilon}$ from 10^{-5} to $10^{-2} s^{-1}$). A time dependant term can be added to the kinematic hardening, to model stress relaxation and also creep. Nevertheless, it is easier to add a second potential to the model which is only viscoplastic to consider low strain rate (typically $\dot{\varepsilon}$ from 10^{-9} to $10^{-5} s^{-1}$).

Two different expressions will be used for viscosity, each one associated to a plastic strain. One is said to be “fast” (8) and the other one to be “slow” (9):

$$\dot{p}_f = \left\langle \frac{J_2(s - X) - R_0}{K_f} \right\rangle^{n_f} \quad (8)$$

$$\dot{p}_s = \left\langle \frac{J_2(s)}{K_s} \right\rangle^{n_s} \quad (9)$$

The stress considered for the slow potential doesn't have any threshold. That means that from low

stress to high stress, the model shows creep strain. An alternative to achieve this result is to use static recovery in the kinematic hardening, but if the yield stress is too high the model won't be able to model creep at low stress levels.

3. Incremental damage law based on stored energy

As explained in the introduction of this paper, the life of a part under cyclic loading is decomposed in two parts: first the time before initiation of microcracks or porosities (depends of the loads) and then a phase when these defects grows until the breaking of the part. As it is usually considered, the time before initiation stands for 90% of the total life time of the part. So in this article, we will only model the time before initiation through the computation of energy stored by hardenings.

3.1. Original framework

3.1.1. Threshold definition

While classical model of life prediction cannot avoid the notion of cycle; energetic framework allows it with an advantage to take into account complex cycles. The figure 1 defines the existence of a threshold in stored energy, which can be identified by means of a typical monotonous traction test or creep test. The energy stored by hardenings allows defining this threshold, noted ω_D and can be written as the sum of the energy stored by isotropic hardening (R) and that stored by kinematic hardening (X) [6]. This threshold is considered as a material parameter.

$$\omega_D = AR_\infty p_D^{1/m} + \frac{X_\infty^2}{2C} \tanh^2\left(\frac{\gamma \Delta \epsilon_p}{2}\right) \quad (10)$$

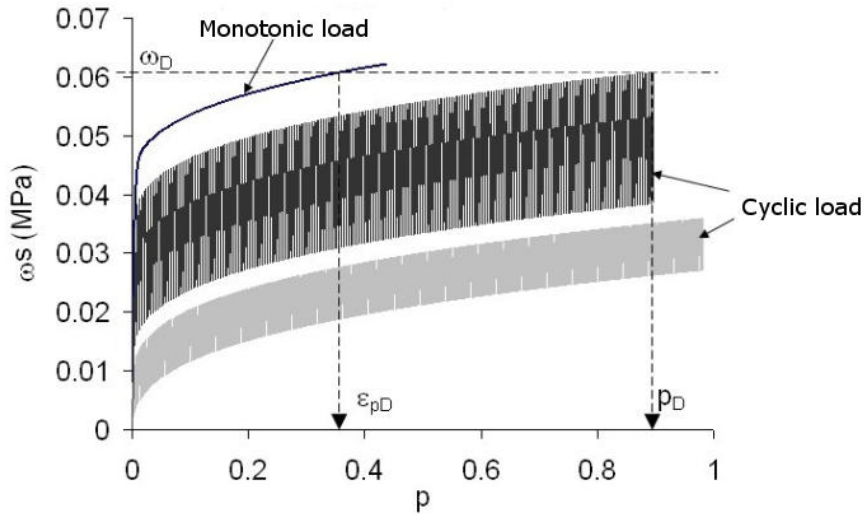


Figure 1: stored energy threshold for different kind of loads [6]

with

$$p_D = \left[\epsilon_{p_D}^{1/m} + \frac{X_\infty^2}{2AR_\infty C} \cosh^{-2}\left(\frac{\gamma \Delta \epsilon_p}{2}\right) \right]^m \quad (11)$$

As the threshold is defined, we have now to define the plastic strain energy accumulation method that allows attaining the threshold.

3.1.2. Stored energy model

The energy stored by hardenings is defined by the integral over time that follows

$$\omega_s = \int_0^t (R\dot{r} + X_{ij}\dot{\alpha}_{ij}) dt \quad (12)$$

considering an elasto-viscoplastic model with an isotropic and a non linear kinematic hardening.

This definition implies a monotonic growth of stored energy. Nevertheless, experimentally [8] a tendency to saturation appears. A correction of the expression is then necessary.

$$\omega_s = \int_0^t (R(r)z(r)\dot{r} + X_{ij}\dot{\alpha}_{ij}) dt \quad (13)$$

with $z(r)$ the correction function.

As the stored energy is defined as a temporal function, it is possible to do an incremental calculation of the stored energy. It is preferable to be able to compute the stored energy independently from the behavior model which is chosen, so a stress equivalent formula will be used:

$$\omega_s = \int_0^p \langle \sigma_{eq} - \sigma_y \rangle z(p) dp \quad (14)$$

It is important to note that the choice of the saturation function is critical for the life prediction. The next part presents some models in order to render at best the behavior of the material.

3.1.3. Stored energy computation

This method has been implemented in the FE software Zset¹ as a post processing. First a behavior calculation is performed in order to determine plastic strain and stress, then the post processing is applied on the whole history and gives a life prediction.

The stored energy expression can be transformed as follow:

$$\omega_s = \int_0^p \langle \sigma_{eq} - \sigma_y \rangle z(p) dp = \int_0^p \langle \sigma_{eq} - \sigma_y \rangle d(Z(p)) \quad (15)$$

$$\text{with } \frac{dZ(p)}{dp} = z(p) \quad (16)$$

By discretization comes the stored energy at time t+1:

$$\omega_{s_{n+1}} = \omega_{s_n} + \langle \sigma_{eq-\sigma_y} \rangle_{n+1} (Z(p_{n+1}) - Z(p_n)) \quad (17)$$

and

$$p_{n+1} = p_n + \sqrt{\frac{2}{3} d\epsilon^p_{n+1} : d\epsilon^p_{n+1}} \quad (18)$$

With the proposal for a new material parameter, the stored energy threshold, ω_D , the life prediction of a specimen becomes possible. The last function to determine is then $Z(p)$.

¹ Developed by Northwest Numerics, ONERA and l'école des Mines de Paris Paristech.

The function proposed by [9], [6] has two parameters and is written:

$$Z(p) = Ap^{\frac{1}{m}} \quad (19)$$

It allows saturating the store energy like in figure 2.

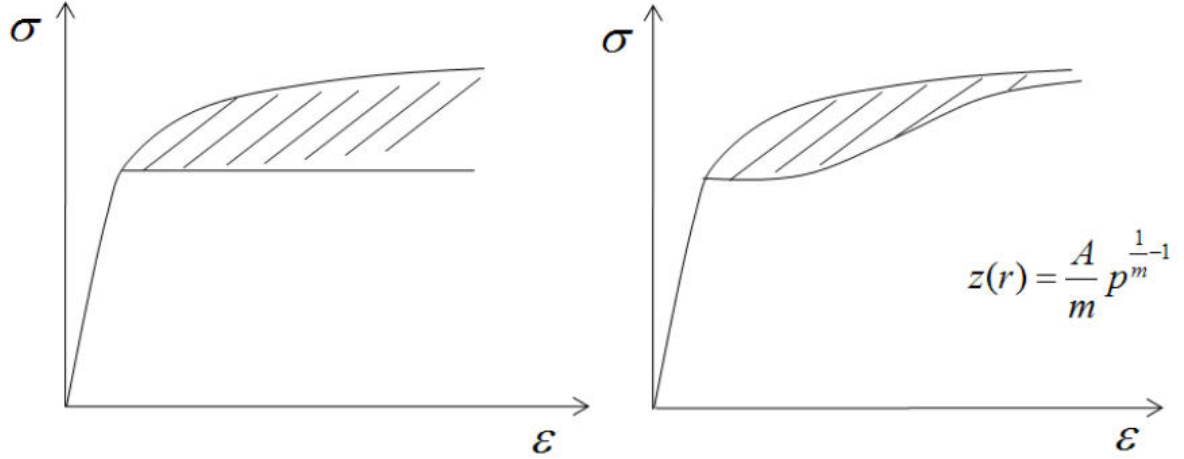


Figure 2: energy stored by hardenings without correction (on the left) and with correction (on the right) to saturate the maximum stored energy (hatched on the figure) [6]

Nevertheless, with this accumulation model it is impossible to take into account correctly the slope of the S-N curves. Roxane Marull, in her Thesis, proposed a new correction function that allows modeling the experimental data, mainly for HCF fatigue regime at high temperature. The model is divided in two parts: one for creep damage and the other one for fatigue damage. It writes:

$$\Delta\omega_s = \langle \sigma_{eq} - \sigma_f \Delta Z(p) \rangle \quad (20)$$

With σ_f the material endurance limit and $Z(p)$ defined by:

$$Z(p) = p, \quad p \leq \varepsilon_{p_D} \quad (21)$$

$$Z(p) = \frac{1}{1 - \frac{2}{\pi} \arctan(p - p_D^0)} + \varepsilon_{p_D} + \frac{1}{1 - \frac{2}{\pi} \arctan(\varepsilon_{p_D} - p_D^0)}, \quad p > \varepsilon_{p_D} \quad (22)$$

The first part of the accumulation model is used to model monotonic loads. The second allows to represent the arctangent form of fatigue experimental data observed in the diagram (σ, p_D) . The parameters p_D^0 , σ_f , and σ_u are identified accordingly to figure 3. σ_u is defined as the static stress to rupture, σ_f is the endurance limit, finally p_D^0 represents the inflexion point of the curve.

The stored energy is function of cumulated plastic strain. The two steps that are used in the model to model monotonic loads and fatigue loads (respect to the parameter ε_{p_D}) makes the coupling between the two phenomenon too weak to model high temperatures fatigue data.

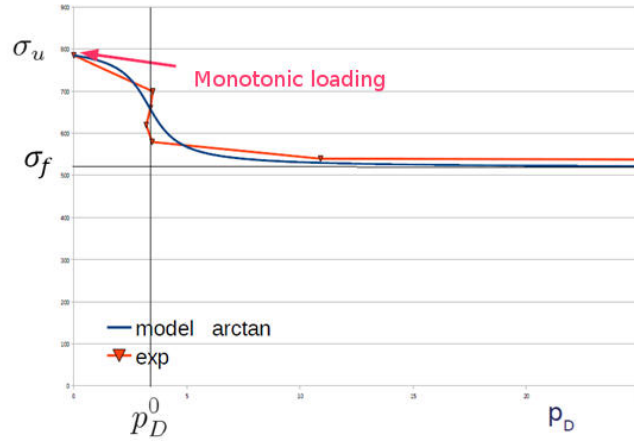


Figure 3: identification procedure of arctangent accumulation model

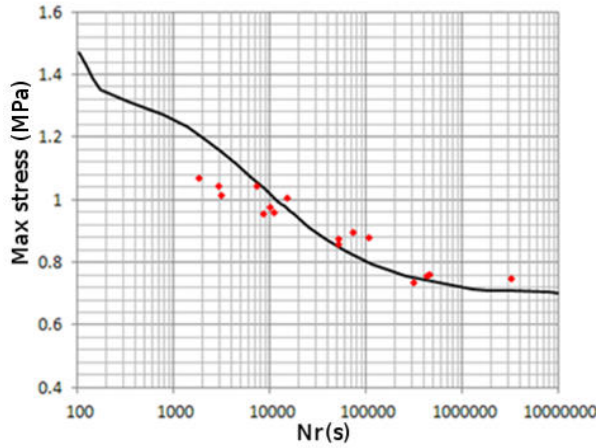


Figure 4: S-N curve for Ha188 at 900°C, $R_\sigma = -1$, $f=0.5\text{Hz}$

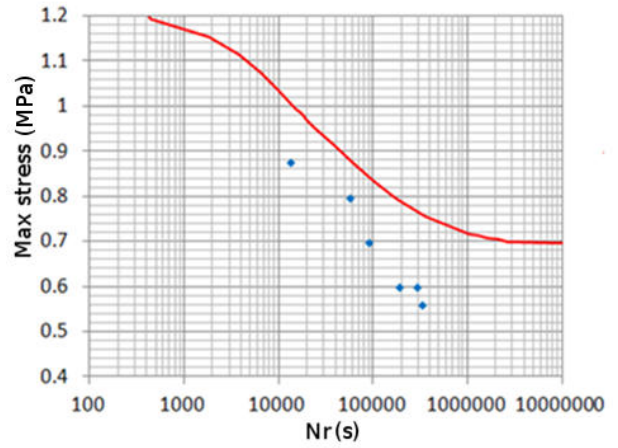


Figure 5: S-N curve for Ha188 at 900°C, $R_\sigma = 0$, $f=0.5\text{Hz}$

The figure 4 and 5 shows that it is impossible to find a set of parameters that fits experimental data for different R ratio. The damage at $R_\sigma = -1$ is too important comparing to $R_\sigma = 0$. This R ratio effect is mainly due to creep damage, so a more coupled version of the model has to be designed.

3.2. Modification of the computation of energy stored by hardenings

The new proposition intends to model correctly creep fatigue interaction. So as the behavior law has two potentials: slow and fast, the damage model has to use it. Instead of modeling monotonic and fatigue damage sequentially considering one source of plasticity, we will consider the slow plasticity potential for creep damage and fast plasticity potential for fatigue damage. The energy increment becomes:

$$\Delta\omega_s = \langle \sigma_{eq} - \sigma_f \rangle \Delta Z_r(\epsilon_r^p) + \langle \sigma_{eq} \rangle \Delta \epsilon_{l,eq}^p \quad \text{if } \Delta\omega_s > 0 \quad \text{else } \Delta\omega_s = 0 \quad (23)$$

With

$$\Delta Z_r(\varepsilon_r^p)_{n+1} = \frac{1}{1 - \frac{2}{\pi} \arctan(A(\varepsilon_{r_{eq_{n+1}}^p} - \varepsilon_D^0))} - \frac{1}{1 - \frac{2}{\pi} \arctan(A(\varepsilon_{r_{eq_n}^p} - \varepsilon_D^0))} \quad (24)$$

With the cumulated plasticity increment

$$\Delta \varepsilon_{n+1}^p = \varepsilon_{n+1}^p - \varepsilon_n^p \quad \text{and} \quad \varepsilon_{eq}^p = \sqrt{\frac{2}{3} \varepsilon^p : \varepsilon^p} \quad (25)$$

One has to note that in this model the cumulated plastic strain is no longer used but a norm of the tensor of plastic strain is. This is to be able to reproduce the R ratio effect correctly.

3.3. Extension to anisothermal calculations

In the presented model, the life of a part depends on the value of the stored energy threshold, itself depending on the temperature. To allow anisothermal calculations of life times, the stored energy increment is adimensionned by the value of the threshold. So, with the same approach as previously, the expression of this increment becomes:

$$\Delta \omega_s = \frac{\langle \sigma_{eq} - \sigma_f \rangle \Delta Z_r(\varepsilon_r^p) + \langle \sigma_{eq} \rangle \Delta \varepsilon_{l_{eq}}^p}{\omega_D(T)} \quad \text{if} \quad \Delta \omega_s > 0 \quad (26)$$

The energy stored by hardening has then the form of a damage, varying between 0 and 1. If $\omega_s = 1$, then the part breaks.

4. Results

The results will be shown at 950°C for AM1 and at 800°C for Ha188. These two temperatures have been chosen because of a high creep fatigue interaction. In order to compute the life of a specimen, a behavior calculation is done until stabilization (100 cycles), then during the life time post-computation, the whole cycle is passed once in the post processing and then the last cycle is repeated. That means that only few cycles have to be computed in order to get the results even if the model is incremental.

4.1. Creep modeling

The figure 6 presents the comparison between experiments (modeled with a power function) and simulation for Ha188 at 800°C. The correlation is good.

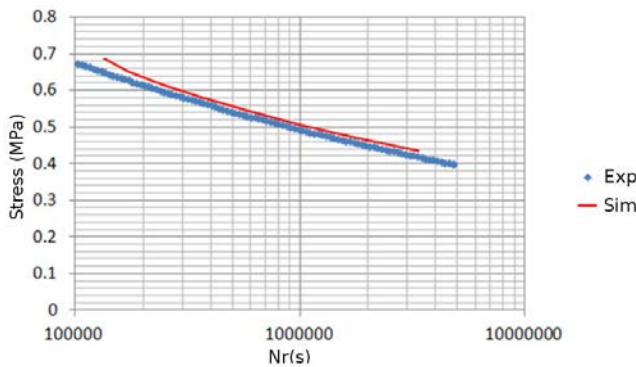


Figure 6: Numerical simulation of creep test to rupture at 800°C for Ha188. (Experiments are modeled with a power function)

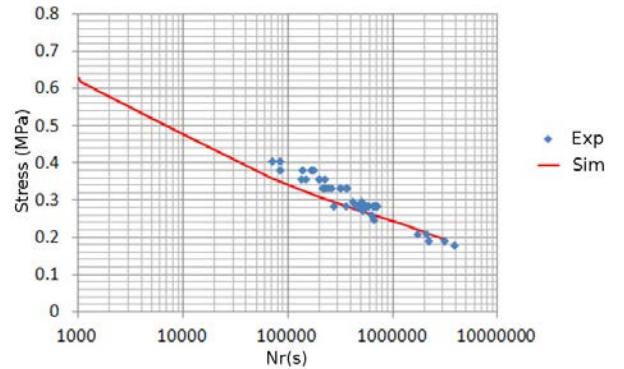


Figure 7: Numerical simulation of creep test to rupture at 950°C for AM1

The same plot has been done at 950°C for AM1 on figure 7. On both cases, we can see that there is a small mismatch between experimental results and numerical simulation. As the behavior law has only been identified on secondary creep, the model overestimates the life. A correction can be made with the threshold ω_p . But a compromise is to be found with fatigue damage.

4.2. Fatigue modeling

In order to show that the model represents well the R ratio effect, two curves are plotted for each material. A $R_\sigma = -1$ and a $R_\sigma = 0$ curve for each material. As no ingredients have been added in the damage model to represent this effect, one can see that it is well described on the following figures. Moreover, the slopes of the different curves are quite different. This is because the behavior model, as well, as the damage model combines too give the right life time of specimens.

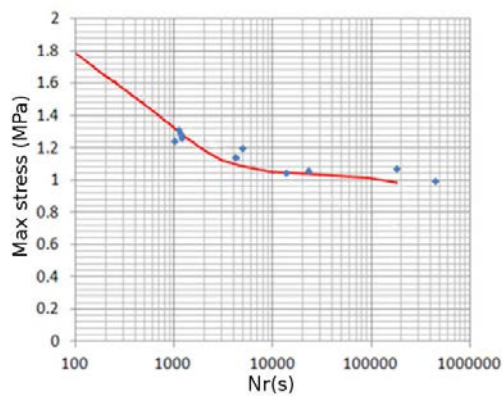


Figure 8: S-N curve for Ha188 at 800°C, $R_\sigma = -1$, $f=0.5\text{Hz}$

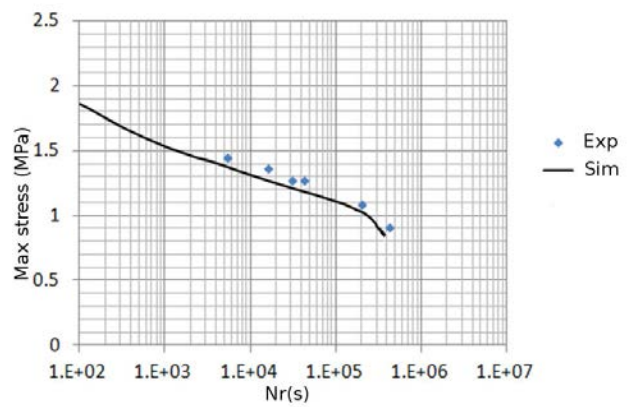


Figure 9: S-N curve for Ha188 at 800°C, $R_\sigma = 0$, $f=0.5\text{Hz}$

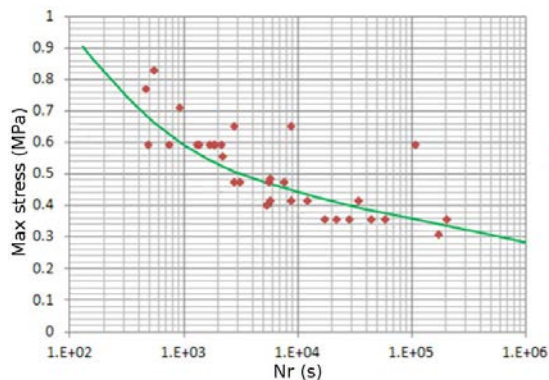


Figure 10: S-N curve for AM1 at 950°C, $R_\sigma = -1$, $f=0.5\text{Hz}$

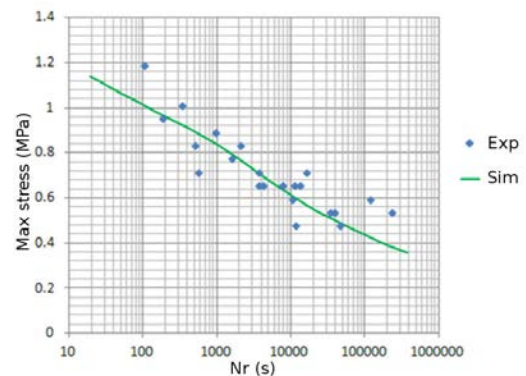


Figure 11: S-N curve for AM1 at 950°C, $R_\sigma = 0$, $f=0.5\text{Hz}$

4.3. Limitations

We have seen in the previous parts that the high temperature life of specimen is reproduced very well. Nevertheless, the model is unable to predict correctly room temperature test data. In fact at low temperature, the behavior of the material is more elastic, mainly for HCF data.

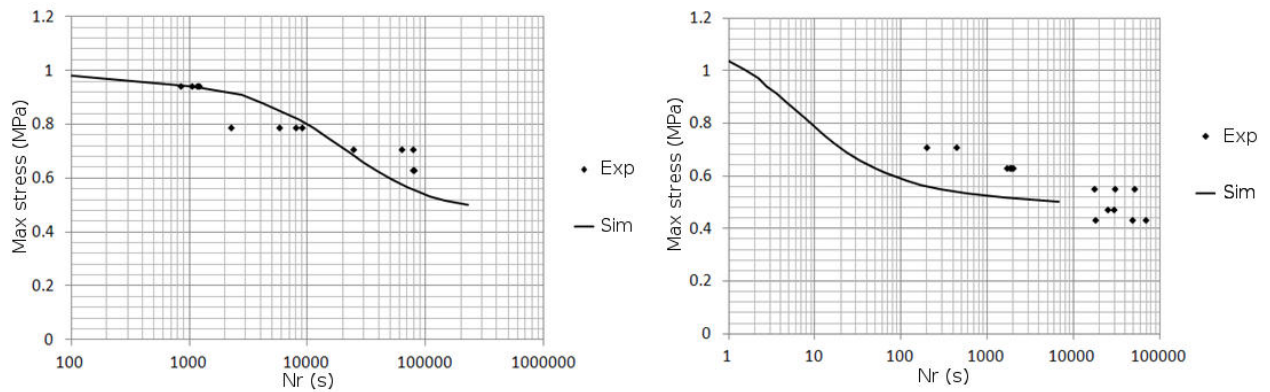


Figure 12: S-N curve for Ha188 at 20°C, $R_\sigma = 0$ on the left and $R_\sigma = -1$ on the right, $f=80\text{Hz}$

It is obvious on figure 12 that the model has some difficulties to represent the R ratio effect at low temperatures. The macroscopic plasticity doesn't explain the life of specimen at low temperature. A second scale (microscale damage) should be introduced in the model to represent low temperature behavior.

5. Conclusion and prospects

High temperatures results shown in this article are quite good. Two main aspects can be outlined. First at high temperature, where the influence of "slow" viscosity is great, the model predicts life time in agreement with experimental results with a low number of parameters (A and ε_D^0). Secondly, at low temperatures, the model is able to predict the life of specimens but less accurately. The main reason is a lack of macroscopic plasticity. There is no plasticity shown by the behavior law for high life time HCF tests.

The incremental formulation of the model is a critical advantage comparing to life model that only use cycles and miner law. Here, without a non linear summation between creep damage and fatigue damage, the model represents well the interaction between both phenomenon.

In perspective, this model has to be completed by a microscale damage model in order to be able to represent damage correctly at all temperatures. A way to use the model would be to set the stored energy at zero for low temperatures. But sometimes during anisothermal cycles, the damage can be done at low temperatures. Therefore, this could be non conservative in some case.

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