FAST DETERMINATION OF THE INFLUENCE OF A PLASTIC PRE-STRAIN ON THE HIGH CYCLE FATIGUE PROPERTIES OF STEEL SHEETS FROM SELF-HEATING MEASUREMENTS

Rémi Munier [a,b] , Cédric Doudard [a], Sylvain Calloch [a], Bastien Weber [b]

[a] Laboratoire Brestois de Mécanique et des Systèmes (LBMS), Ensta-Bretagne/UBO/ENIB, 29200 Brest, France
[b] ArcelorMittal Maizières Research & Development, Maizières-les-Metz, France

Abstract. The high cycle fatigue (HCF) is a major element for a great design of automotive parts. A wide part of the steel sheets for the automotive industry are stamped, sometimes deeply. During this operation, the steel is plastically strained in different directions, so that a good prediction of the fatigue behavior requires the determination of the fatigue properties of the pre-strained material. Nowadays, the evolution of HCF properties is often neglected. There are two major reasons for this lack. On the one hand, a good finite element simulation of the forming operation to predict pre-strain field is still a difficult task. On the other hand the time dedicated to traditional fatigue test campaigns (e.g. staircase method) to quantitatively identify this influence is prohibitive. To determine faster this influence, it is proposed to use self heating measurements under cyclic loadings. By using a two scale probabilistic model, based on the progressive microplasticity appearance that takes into account the influence of a plastic pre-strain, it is possible to predict the evolution of the fatigue properties with the pre-strain. A wide range of plastic pre-strain is under investigation that demonstrates the ability of the method to account quickly for the HCF properties evolution.

1 INTRODUCTION

The parts of the structure and the chassis frame of a car are designed by taking into account the Low Cycle or High Cycle Fatigue mission. Concerning the high cycle fatigue regime, parts obtained from steel sheets are subjected to primary forming operations (stamping, bending …). During these drawing operations, the steel is sometimes severely strained according to different directions or strain paths inducing thickness and cumulated plastic strain variations [1]. In other words the material has changed and its current fatigue properties are no more the same as initial ones. For example, traditional fatigue campaigns have been applied to the Dual Phase steel. The S-N curves (Stress-Number of cycles) show that the fatigue properties of the pre-strained material to 20% are higher than without (Fig. 1) at a load ratio R=-1 (*i.e.*, with a zero mean stress). The initial endurance limit of 250 MPa increase to 320 MPa after the applied pre-strain. A reliable fatigue life prediction requires thus a good determination of these new fatigue properties caused by the pre-strain.

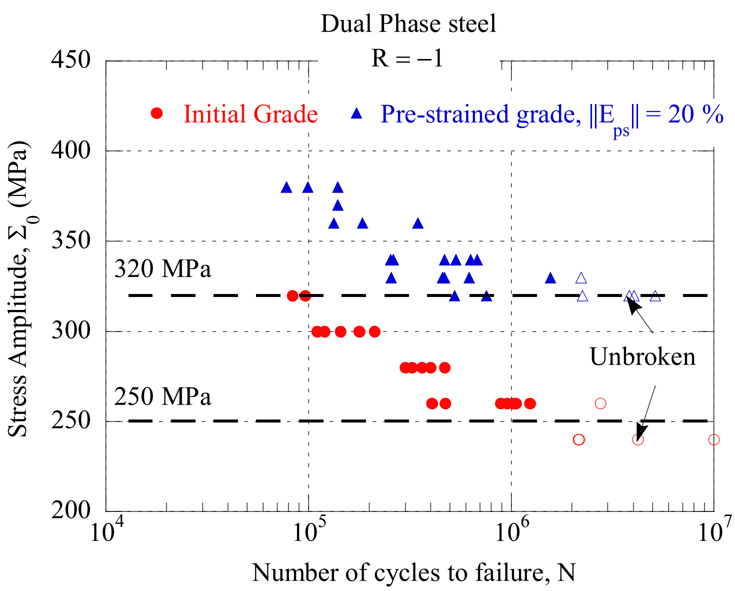

Figure 1 : Influence of a plastic pre-strain on the HCF properties a dual phase steel.

A plastic pre-strain has thus a great influence on the HCF properties of steel grades [2-4] but is not taken into account in classical fatigue design. One of the major reasons of this lack is the prohibitive time dedicated to traditional fatigue campaigns: one month and 25 pre-strained specimens to plot a complete Wöhler curve, only for one level of plastic pre-strain. A reliable fatigue life prediction requires the determination of one S-N curve for several levels of plastic pre-strain.

In order to free oneself from these issues, self-heating measurements are used [5-10]. The main goal of the proposed approach is to predict the evolution of HCF properties of steel grades with the plastic pre-strain. To establish the dialogue between self-heating measurements, a two scale probabilistic model that takes into account the influence of a plastic pre-strain is used. This study is limited to 1D cases.

In a first phase, the principle of self-heating measurements is presented that puts in obvious the existence of two microplastic regimes on the self-heating curves. The two scale probabilistic model that establishes the dialogue between self-heating measurements and fatigue properties is then briefly presented. In a second phase, the steel grades are subjected to a plastic pre-strain in tension mode which leads to change the thermal response observed by self-heating measurements. These changes observed on the self-heating curves permits to predict the HCF properties evolution for not only high levels of plastic pre-strain but also low levels. An incontrovertible way of validation consists in performing traditional fatigue tests at different levels of plastic pre-strain.

2 SELF-HEATING MEASUREMENTS

2.1 Principle of the test

The principle of the proposed approach is a fast identification of the HCF properties of steel grades. It is based on the following of the temperature evolution of a specimen under cyclic loading. The specimen is a sample with a width of 10 mm a length of 120 mm, the thickness being the one of the sheet. During the test, only 50 mm are let between the grips of the hydraulic tension machine. In the all study, a 0D approach is used, which implies that the mean temperature of the specimen is representative of the steel grade behavior. For one level of loading consisting in a block of 6000 cycles at a load frequency fr of 30 Hz, Fig 2a) shows the temperature evolution (noted θ that is the difference between the temperature of the specimen and the surrounding value $\theta = T_{specimen} - T_0$) during these 200 seconds of cyclic loading. After a transitory phase with a progressive temperature elevation, the temperature reach a stabilized level of temperature noted $\bar{\theta}$.

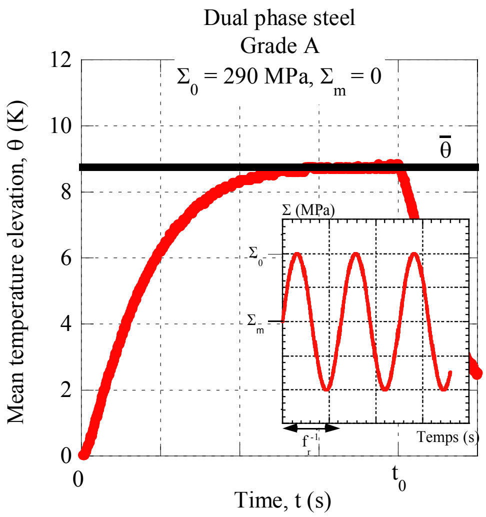

Figure 2: Temperature evolution during 6000 cycles at a load frequency of 30Hz for a dual phase steel.

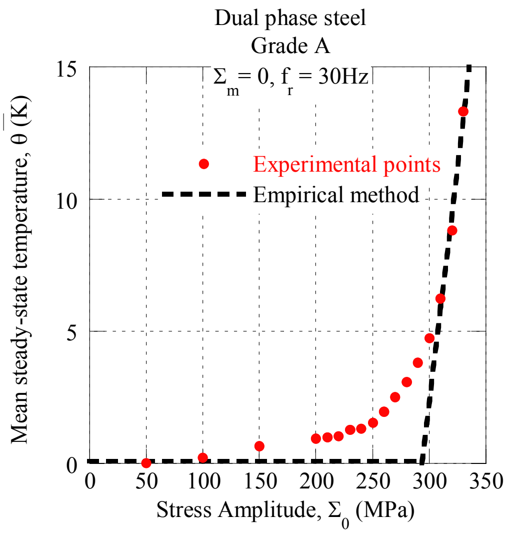

Figure 3: Self-heating curve of a dual phase steel at a load ratio of R=-1.

For a complete self-heating test, successive series of cyclic loading, with increasing levels of stress amplitude are applied to the specimen. For each level of cyclic loading, the mean steady-state temperature can be determined. At the end of the test, a self-heating curve (Fig. 3) can be plotted representing the mean steady-state temperature relating to the stress amplitude. A low temperature elevation is observed for low amplitudes of cyclic loading whereas a progressive temperature rise is obtained for higher ones. From this curve, an empirical method for the determination of the mean endurance limit of the steel grade is to perform a linear regression on the last points on the curves. The intersection between that straight line and the abscissa axis gives a good estimation of the steel grade fatigue limit.

2.2 A two scale probabilistic model with two microplastic regimes

According to the results obtained on a wide range of steel grades, it is possible to decompose the curve into two microplastic regimes. Fig. 4 shows a logarithmic representation of the self-heating curves for the grade of interest in this study. The two microplastic regimes are put in obvious on this curve. For low amplitudes of cyclic loading, the presence of a primary regime can be noticed. This primary regime is always observed having a slope of two on all steel sheet grades. It corresponds to a microplastic regime, due to a restoration mechanism that implies a competition between creation and annihilation of dislocations inside of the steel.

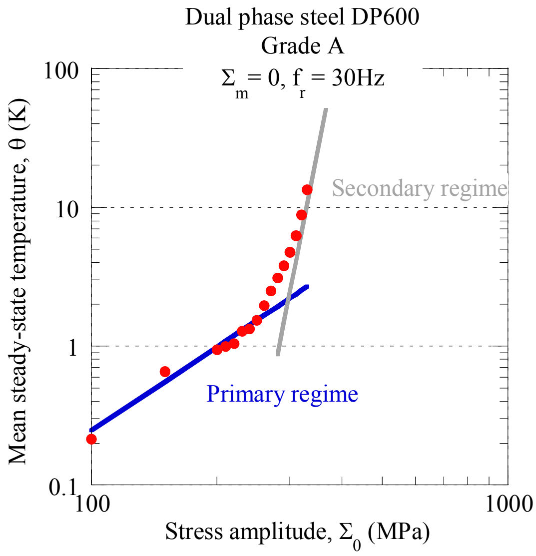

Figure 4: Logarithmic representation of the Grade A self-heating curve.

The secondary regime corresponds to a progressive appearance of microplasticity and is different from one grade to one other. During fatigue tests, this microplastic regime leads to the emergence of Persistent Slip Bands (PSB) on the surface of the steel [12]. These observations and the acquired experience permits to put in place a two scale probabilistic model [10-11]. Its role is to establish a dialogue between self-heating curves and Wöhler curves in order to predict the HCF properties from self-heating measurements.

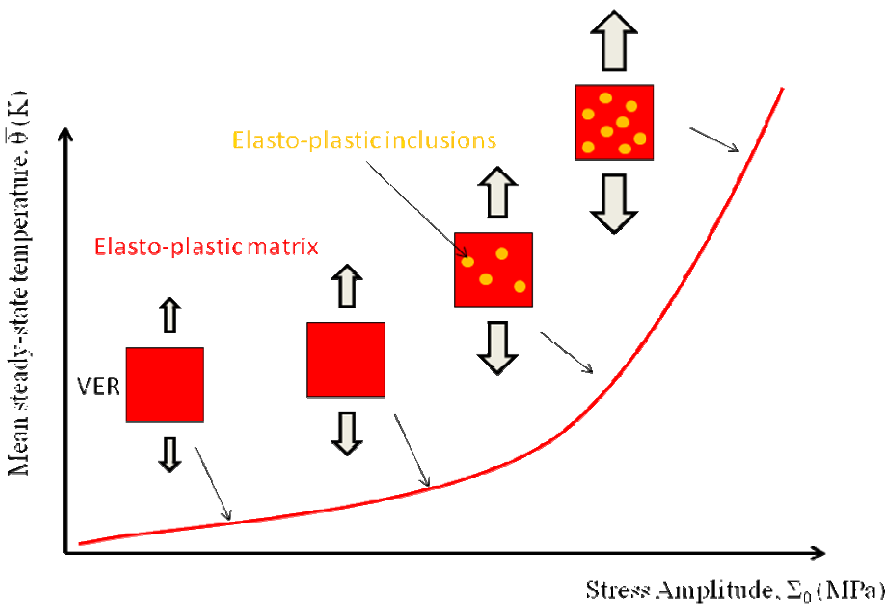

Figure 5: Evolution of the VER with an elasto-plastic matrix and a population of inclusions regarding to the temperature evolution with the stress amplitude.

For the two scale probabilistic model, the Representative Elementary Volume is composed by a matrix and a population of inclusions (Figure 5). Both matrix and inclusions own a plastic behavior, a non linear kinematic hardening for the matrix and a linear kinematic hardening for inclusions. The activation of the inclusion is defined by using a Point Poisson Process [13-14] that is a function of the stress amplitude Σ_0. Thus the number of active sites (N) in *a* Ω domain having a volume V is given by

$$N(\Omega) = \lambda \times V \text{ with } \lambda = \frac{1}{V_0}\left(\frac{\Sigma_0}{S_0}\right)^m ,$$

with λ the intensity of the process, V_0 the volume of the sites, m the Weibull's modulus and S_0 the Weibull's scale parameter.

Thus, with this two scale probabilistic model, the intrinsic dissipation Δ can be calculated and is given by

$$\Delta = \alpha_\Delta (\Sigma_0)^2 + \delta_\Delta (\Sigma_0)^{m+2},$$

with α_Δ and δ_Δ material parameters that depend on the hardening of the matrix and on the activation of the inclusions.

2.3 Description of self-heating curves

By using a 0D approach, the 0D heat conduction equation can be written as [11]

$$\dot{\theta} + \frac{\theta}{\tau_{eq}} = \frac{f_r}{\rho C}\Delta,$$

with f_r the loading frequency, ρ the mass density, C the specific heat, τ_{eq} the characteristic time for the return at thermal equilibrium (that takes into account the loss by conduction into the grips and the loss by convection). By solving this heat conduction equation, it is possible to write the mean steady-state temperature as a function of the stress amplitude by

$$\bar{\theta} = \alpha \times \Sigma_0^2 + \delta \times \Sigma_0^{m+2}$$

with α and δ material parameters.

One of the main trumps of this model is that the entire self-heating curve is used for the identification of the parameters, on the contrary to the model of [11] that uses only the last points of the curve. The results of the identification are shown on the Fig. 6. Both primary and secondary regimes are very well described.

2.4 Prediction of Wöhler's curves

In order to define the unlimited fatigue life, the weakest link theory is used, which considers that failure appends as soon as one site is activated. Thus, the probability to find k active sites (P_k) in a volume V follows a Poisson distribution

$$P_k(V) = \frac{(\lambda V)^k}{k!}\exp(-\lambda V).$$

The probability of failure which corresponds to the probability to find at least one active site in the volume is then given by

$$P_F = 1 - \exp\left(-\frac{V}{V_0}\left(\frac{\Sigma_0}{S_0}\right)^m\right).$$

In this case, it is possible to define the mean endurance limit and the associated standard deviation given by

$$\bar{\Sigma}_\infty = S_0\left(\frac{\mathrm{V_0}}{\mathrm{V}}\right)^{\frac{1}{\mathrm{m}}}\Gamma\left(1 + \frac{1}{\mathrm{m}}\right),$$

with $\Gamma(p) = \int_0^\infty t^{p-1}e^{-t}dt$ the Euler Gamma function. Thus, the mean endurance limit depends only on the Weibull's parameters [15-16].

The description of limited fatigue properties (in order to describe the isoprobabilities of failure) is provided by the use of an energetic criterion defined by

$$N = \frac{A}{\Sigma_\infty(P_F)\langle\Sigma_0 - \Sigma_\infty(P_F)\rangle},$$

with A a material parameter that is defined by using 5 specimens to failure at a high stress amplitude, about 100 000 or 200 000 cycles to failure (the other bound is provided by the mean endurance limit obtained from self-heating measurements), and $\Sigma_\infty(P_F)$ the endurance limit for a given probability of failure.

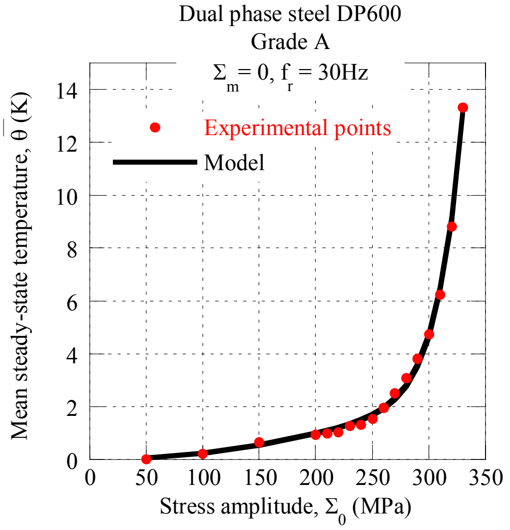

Figure 6: Identification of the model's parameters on the self-heating curve of the grade A.

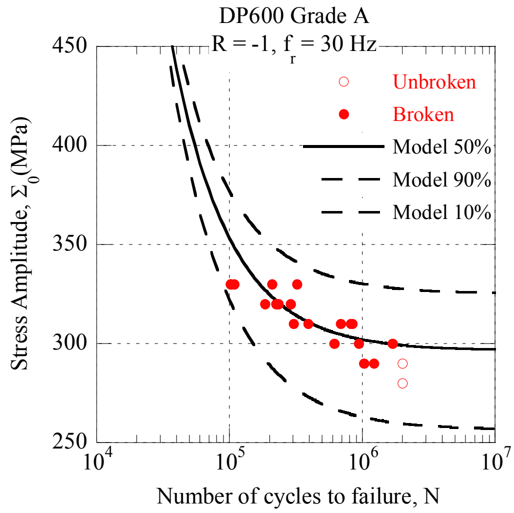

Figure 7: Wöhler curve of the grade A at R = -1 from self-heating measurements and comparative with experimental points.

The validation of the model is made on the two grades by a comparison with the experimental points and the results given by the model. To plot the Wöhler curve from self-heating measurements, only 3 days, one self-heating specimen and 5 fatigue specimen are required on the contrary to standard characterization that is more time and specimen consuming (one month and 25 specimens). The comparative of the S-N curves is given in the Fig. 7. A good agreement is observed, nevertheless, an overestimation of the standard deviation is obtained from self-heating measurements.

3 EFFECT OF A UNIAXIAL PLASTIC PRE-STRAIN

A plastic pre-strain has a great influence on the HCF properties of steel grades. The aim is here to use self-heating measurements on pre-strained specimens, to observe the evolution of self-heating curves and finally to predict the HCF properties evolution. In this paper, only the influence of a uniaxial plastic pre-strain is under interest.

3.1 Influence on self-heating curve and model modifications

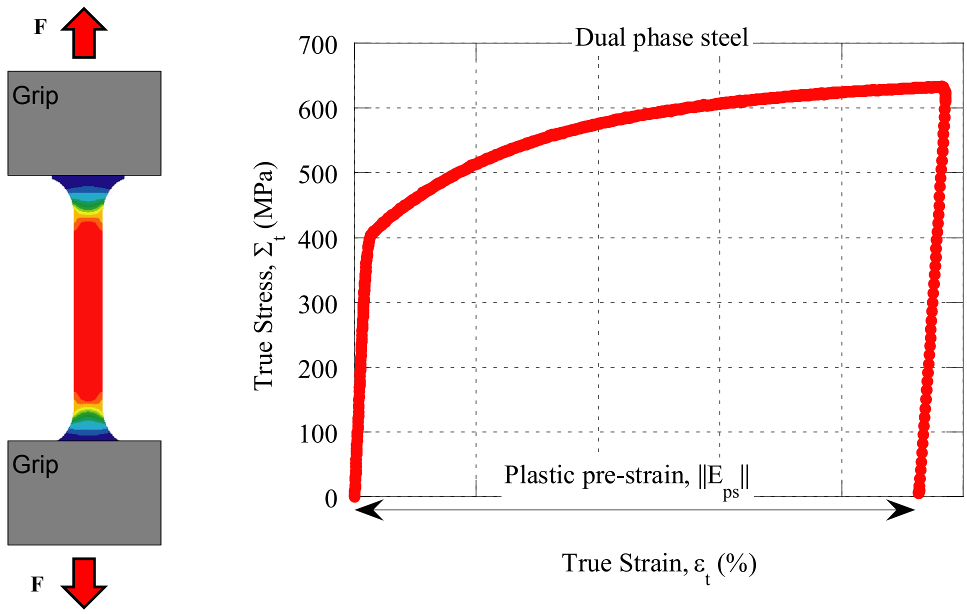

Figure 8: Pre-strain test to reach a given level of plastic pre-strain ||Eps||.

To study the influence of a 1D plastic pre-strain on the self-heating properties, tension specimen are subjected to a tension test where a given level of plastic strain is reached (Fig. 8). Then the position of the specimen in the hydraulic grips is changed to be placed in the self-heating configuration (a gage length of 50 mm between the grips (Fig. 9)). The self-heating procedure is then applied at a load ratio of R = -1.

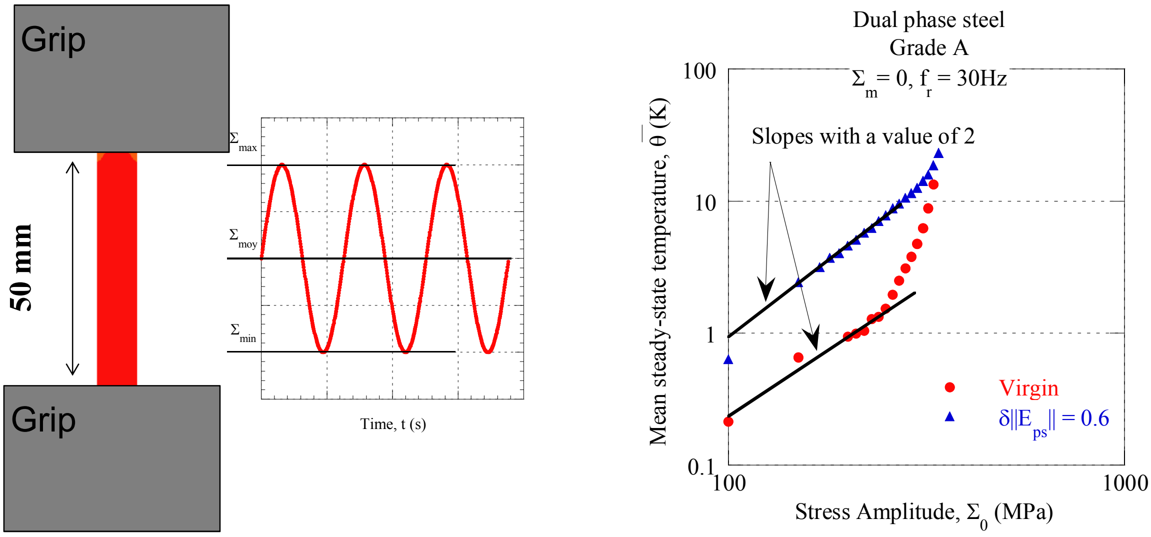

Figure 9: Self-heating test on the pre-strained specimen and comparison with the virgin self-heating curve.

In the following, the plastic strain is noted $||E_{ps}||$ and corresponds to the von Mises equivalent plastic strain given by

$\left\|E_{ps}\right\| = \sqrt{\frac{2}{3}\underline{\underline{E}}_{ps} : \underline{\underline{E}}_{ps}}$. For confidentiality reasons, the level of plastic strain is not explicitly given and is normalized by the maximum level of plastic pre-strain studied. Thus, we define the ratio $\delta||E_{ps}||$ as

$$\delta\left\|E_{ps}\right\| = \frac{\left\|E_{ps}\right\|}{\max\left(\left\|E_{ps}\right\|\right)},$$

that is used on the curves.

The comparative between the self-heating curves of the pre-strained grade (at a ratio of 0.6 in tension mode) and the virgin one is given in the Fig. 9. It can be noticed that the primary regime is all the more higher than for the virgin grade, but still follows a power law with a power of 2. The secondary regime is also impacted by this introduction of a plastic pre-strain. In order to take account for these changes experimentally observed, it is necessary to introduce into the model a dependency to the plastic pre-strain. For the primary regime, the dependency concerns the restoring term of the non linear kinematic hardening. For the secondary one, the intensity of the process (that describes the progressive appearance of microplasticity) is modified, and especially the Weibull's scale parameter.

Thus, the mean steady-state temperature can be written (in function of the level of plastic pre-strain) by

$$\bar{\theta} = \alpha\left(\left\|E_{ps}\right\|\right) \times \Sigma_0^2 + \delta\left(\left\|E_{ps}\right\|\right) \times \Sigma_0^{m+2}.$$

Only those two parameters depends on the level of plastic pre-strain, which implies that the Weibull's modulus and the parameter *A* that describes the limited fatigue life are considered as constant.

According to the modification, one quantity is especially under interest, the evolution of the secondary regime that gives data about the HCF properties. Indeed, the choice is made to define the quantity S_{evo} that describes the evolution of the secondary regime observed in self-heating measurements. It is given by

$$S_{evo} = \left(\frac{\delta\left(\left\|E_{ps}\right\| = 0\right)}{\delta\left(\left\|E_{ps}\right\|\right)}\right)^{1/m} = \frac{S_0\left(\left\|E_{ps}\right\|\right)}{S_0\left(\left\|E_{ps}\right\| = 0\right)} = \frac{\bar{\Sigma}_\infty\left(\left\|E_{ps}\right\|\right)}{\bar{\Sigma}_\infty\left(\left\|E_{ps}\right\| = 0\right)},$$

and has the advantage to directly describe the evolution of the mean endurance limit with the plastic pre-strain from the initial state.

3.2 Results

For each steel grade of interest, several levels of plastic pre-strain are under interest. Fig. 10 gives the self-heating curves for several level of plastic pre-strain for the grade A. Even for a very low level of plastic strain, we can note a considerable evolution of the primary regime. Then, this primary regime reaches a stabilized value whereas the secondary regime evolves, with a shift of the self-heating curve with the level of pre-strain.

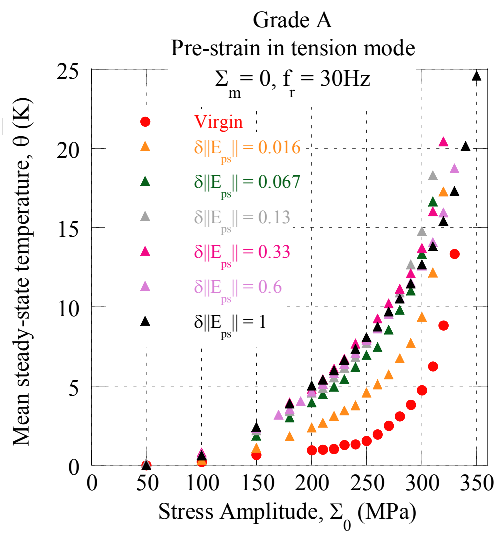

Figure 10: Evolution of the self-heating curves of the grade A with a plastic pre-strain obtained in tension mode.

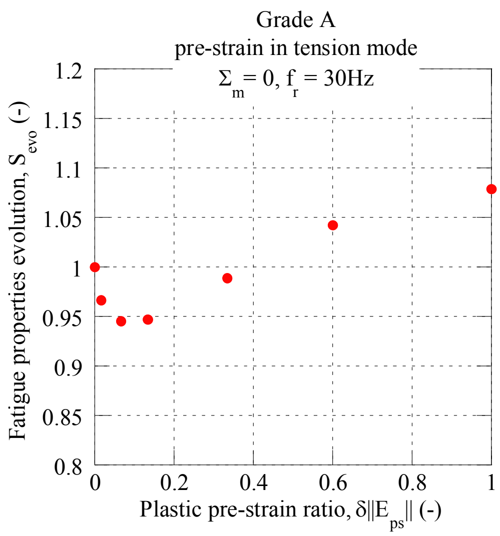

Figure 11: Prevision of the fatigue properties evolution with the plastic pre-strain level for the grade A.

By observing the Fig. 11 that gives the prediction of the HCF properties evolution, a particular evolution can be noticed (a value lower than 1 corresponds to a loss on the HCF properties and higher than an increase). An effective initial loss appends on the first percents of plastic strain with a global minimum. Then after a transitory phase where the curve reaches the initial value, the evolution becomes linear. Thus, an initial loss on the fatigue properties is planned for the first levels of plastic strain and a linear evolution with an increase for higher levels. Each grade has a particular evolution of the HCF properties with the plastic strain, but has always the same aspect with an initial loss.

4 VALIDATION

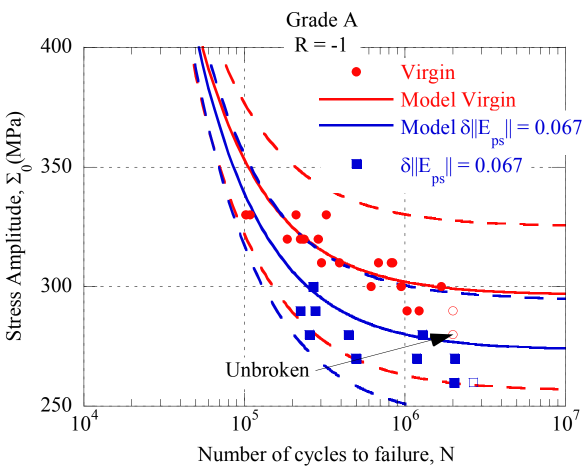

Figure 12: Comparison between the prevision made and the experimental results on the grade A pre-strained at 1%.

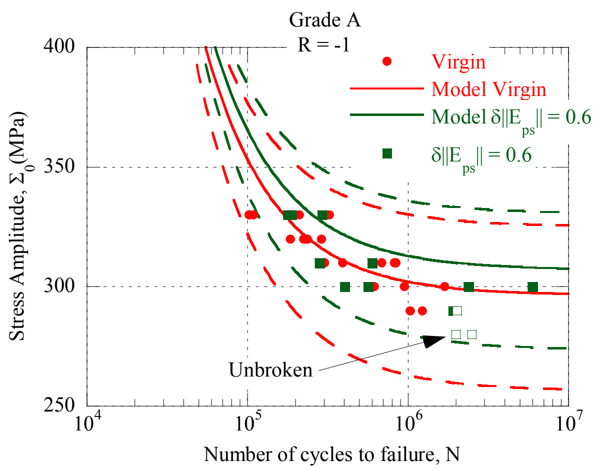

Figure 13: Comparison between the prevision made and the experimental results on the grade A pre-strained at 10%

The validation of the results obtained with self-heating measurements is made by performing fatigue tests on specimens pre-strained in tension mode. Two levels of plastic pre-strain are under consideration, a low one at a ratio of 0.067 in order to validate the loss obtained for low levels of plastic pre-strain, and a high one at a ratio of 0.6. To plot the S-N curve for the pre-strained levels, only the self-heating results are used. No point to failure is required to determine the energetic criterion (the parameter A is supposed to be constant with the pre-strain and equal to the virgin one).

Fig. 12 shows the comparison between the virgin grade and the same one but pre-strained at a ratio of 0.067 in tension mode. The prevision made by self-heating measurements is in good agreement with the experimental points. There is a fatigue properties loss for low levels of plastic strain. For the high level of plastic pre-strain (Fig. 13), the prevision on the fatigue properties increase is weak and difficult to capture with a few specimens by fatigue.

5 CONCLUSION

Self-heating measurements can predict the influence of a plastic pre-strain on the high cycle fatigue properties of steel grades. By using a two scale probabilistic model, S-N curves can be predicted by taking into account the modification observed on self-heating curves with a plastic pre-strain. With this methodology, only one week is required to determine the HCF properties of the virgin steel grades and on a wide range of plastic strain.

Other steel grades have been studied and explanations on the evolution of the fatigue properties with the plastic pre-strain can be given by focusing on the steel hardening. Additionally to these results, the influence of mean stress can also be taken into account by this model, which will be showed during the oral presentation.

Self-heating measurements is thus a method to provide quickly material properties, which authorizes to think about a better design of components regarding to fatigue life.

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