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Formulation of a Physically based Intergranular Creep Damage Model for Austenitic Steels

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ABSTRACT

The aim of this study is to proposed a physically based intergranular creep damage model for numerical simulations on extrapolated situations. A continuum damage formulation is proposed, to evaluate nucleation, growth and coalescence of intergranular creep cavities. Nucleation is based on an empirical law where fraction void rate is proportional to the creep strain rate. Voids growth rate includes the contribution of viscoplastic strain rate of surrounding grains (Gurson) and vacancies diffusion along grain boundaries (Hull&Rimmer). Voids coalescence is based on a mechanical rupture criterion, where the competition between damage softening and viscoplastic hardening is considered. The identification procedure needs the only results of uniaxial creep tensile tests with a range of time to rupture that enables a sufficient diffusion contribution. The constraint effect is take into account in the formulation of the model and doesn't need a specific identification. To illustrates the capacity of the proposed model applications are presented for an austenitic steel at 600°C. It appears that the constraint effect assessment is in good agreement with experimental results, when we compare time to rupture and intergranular damage localisation on notched specimens, or crack initiation time and crack growth rate on fatigue pre-crack specimens.

INTRODUCTION

This study concerns high temperature design rules and remaining life assessment of components containing defects. For austenitic steels high temperature rupture is often due to a creep damage mechanism with intergranular cracks. The more common rules proposed in design codes are : a stress-time rupture curve based on Katchanov criteria for creep crack initiation, and a master curve based on the C* viscous contour integral for defect assessment. Life time evaluation for a real structure leads to extrapolate these criteria, versus loading level and constrained effect, compared to experimental points used for the identification. One major question for extrapolated assessments concerns the competition between diffusion and viscoplastic strain rate contributions in intergranular cavity growth process. In order to answer and validate criteria, representative experimental points (long time to rupture and high stress triaxiality levels) and physically based models are needed.

The aim of this study is to proposed a physically based continuum damage model for numerical simulation on extrapolated situations. In a first part, the model formulation and its background are presented. Parameters identification procedure is also detailed, with an example based on creep rupture properties of 316L(N) austenitic steel at 600°C. In a second part, creep crack initiation and growth assessments are presented on notched and fatigue pre-cracked specimens, in order to illustrate the capacity of the model to take into account constraint effect. Finally, in a third part long time extrapolation is discussed and compared with a global fracture criteria based on C* parameter.

INTERGRANULAR CREEP DAMAGE

Intergranular creep damage phenomenon in austenitic steels has been widely studied from the metallurgical point of view in references [1] and [2]. In both studies, detailed creep cavitations measurements have been achieved on notched specimens in order to quantify the influence of mechanical parameters, stress and strain, in the cavitation process. It appears that the classical three ductile damage steps can also be used for intergranular creep cavitation. Then damage mechanism presented on Figure 1 is decomposed as following :

- micro void nucleation,
- growth of existing voids,
- grain boundary rupture with voids coalescence.

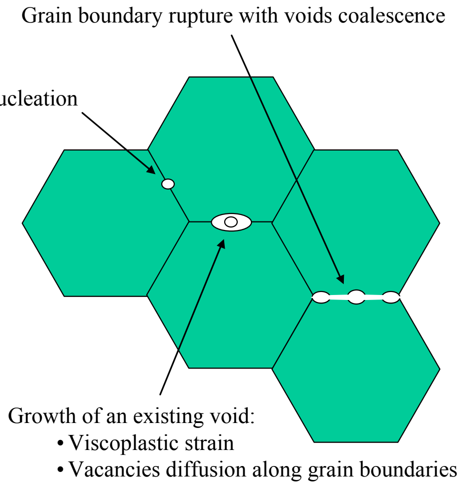

Figure 1 : Intergranular creep damage mechanism in austenitic steels.

The new model formulation proposed in this study is based on the following considerations :

- intergranular creep cavitation is represented by a continuum damage state variable **f**,
- intergranular damage rate equation (1) and coalescence criteria (2) are based on physical foundations (as much as possible),
- there are only two parameters (**Vg** , **A**) to fit nucleation and diffusion rates,
- a quasi unique identification of this two parameters can be derived from uni-axial creep tensile tests,
- the effect of triaxiality, on damage rate **df/dt** and critical void fraction $\mathbf{f_c}$, is explicitely defined in the model and doesn't need to be fitted.

(1)
$$df = V_g . d\varepsilon_f + \frac{3}{2} . f . \sinh\left(\frac{3}{2} . \frac{\sigma_m}{\sigma_{eq}}\right) . d\varepsilon_f + A . \langle \sigma_1 \rangle . dt$$

(2)
$$\frac{\partial \sigma_{eq}\left(\dot{\varepsilon}_f , \varepsilon_f , f_c\right)}{\partial \varepsilon_f} = 0$$

Where $\boldsymbol{\varepsilon_f}$ is the creep strain, $\boldsymbol{\sigma_{eq}}$ the equivalent Von-Mises stress, $\mathbf{3.\sigma_m}$ the first invariant of the stress tensor and $\boldsymbol{\sigma_1}$ the maximal principal stress.

Intergranular creep damage rate is represented by a continuum damage state variable **df/dt** in equation (1). The three additive terms in the latter respectively represent : void nucleation rate, viscoplastic growth rate of existing voids and diffusion growth rate. Nucleation rate is based on an empirical law using macroscopic vicoplastic strain rate. Viscoplastic and diffusion growth rates are respectively derived from the Gurson model [5] and the Hull and Rimmer model [6]. For the latter, the normal grain boundary stress is replaced by the maximal principal stress $\boldsymbol{\sigma_1}$. Then, the parameter **A** doesn't have a direct physical meaning as it includes a scale ratio between local and macroscopic stress states. The homogeneous continuum damage **f** corresponds in fact to an heterogeneous voids distribution at different growth stages. Then, the viscoplastic growth rate is only an approximation of the mean value for the heterogeneous damage field. The Tveergard's modification [8] is not introduced as it is linked to an experimental calibration of the Gurson's yield surface for ductile rupture.

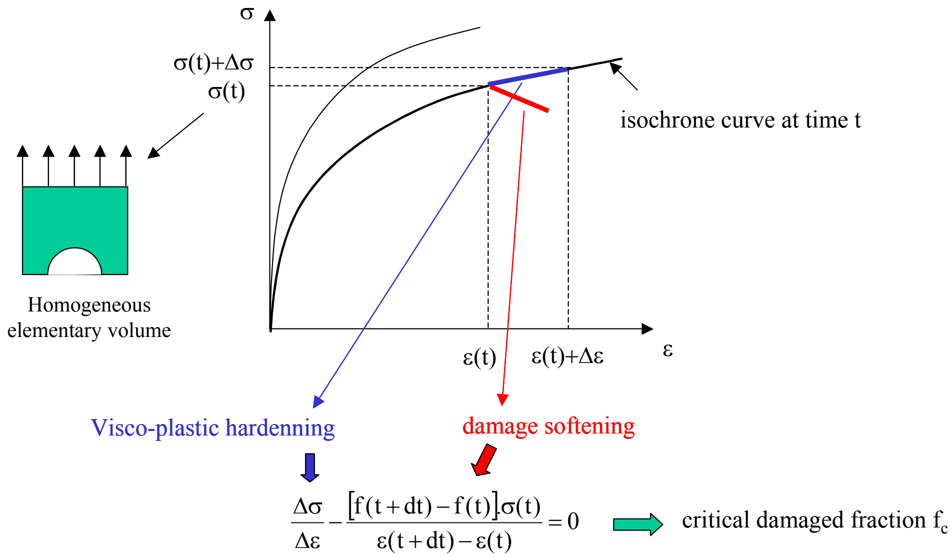

Figure 2 : Mechanical model used for intergranular creep cavities coalescence.

In order to limit the number of parameters, coalescence criterion is based on a simple mechanical model (2). In the latter, intergranular rupture is defined with the maximal stress allowable on damage material (see Figure 2), as proposed in the limit load model of Thomason [9] to describe ductile tearing. In our model, visco-plastic hardening is quantified on an isochronous curve at time t, and damaged softening is derived from a simple balance equation where the section reduction effect is equal to (1 - **f**). In this approach, local stress intensification in damaged material is not taken into account until fraction **f** is lower than its critical value. This choice is consistent with rupture assessment computations, where the creep strain rate is derived from undamaged material properties. In order to have a better estimation of stress redistribution due to intergranular cavitation, before the rupture of boundary grain, this point should be improved in further studies. However, small values of critical damaged fraction (lower than 10%) can justified this simplification.

As presented in equations (1) and (2), there are only two parameters to identify in the model, in order to fit nucleation and diffusion growth rates. As nucleation rate is proportional to creep strain rate, and diffusion is proportional to stress multiplied by time, the latter won't be significant for short rupture times (or high stress level). Then, we can fit unique values for $\mathbf{V_g}$ and **A**, using a two steps procedure with a short time creep rupture test for $\mathbf{V_g}$ and a long time creep rupture test for **A**. According this identification procedure, tests number 1 and 6 of table 1 lead us to the following values : Vg = 0.82, A= 9.10^{-9}.

test number	Nominal stress (MPa)	Time to rupture (h)	Minimal creep strain rate (10^{-6} h^{-1})
1	160	39538	
2	180	34541	1.5
3	200	17122	9.7
4	240	2570	34
5	270	937	84
6	300	321	180

Table 1 : Uniaxial creep rupture tests for 316L(N) steel at 600°C [2].

Concerning numerical aspects of the optimisation procedure, a differential optimisation solver is used with equation (1) and (2). Input data are :

- elasto-plastic hardening curve,

- secondary creep law,
- stress and time to rupture of the tensile test,

output are :

- fitted values of $\mathbf{V_g}$ and **A**,
- critical damage fraction according (2).

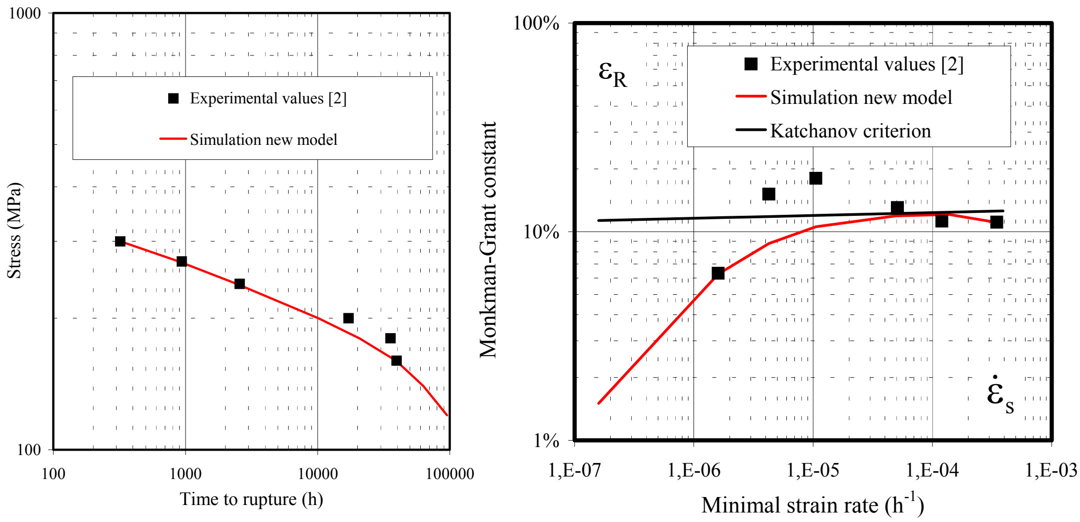

Figure 3 : Tensile creep rupture properties of 316L(N) steel at 600°C.

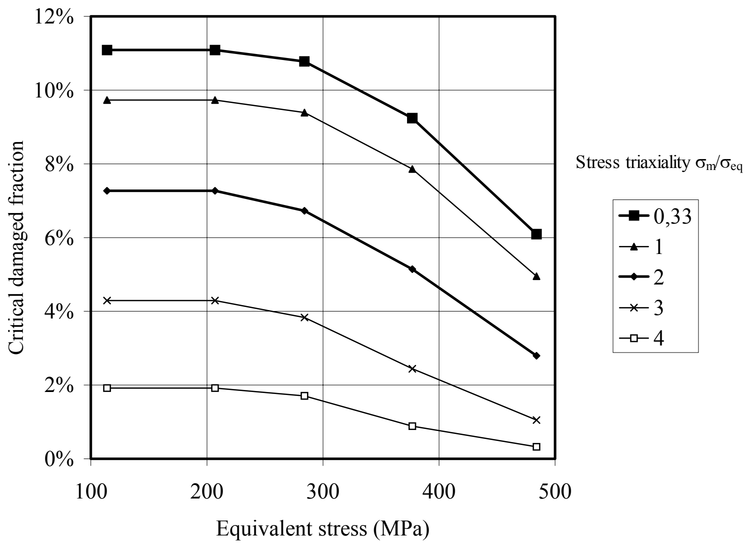

Figure 4 : Critical damaged fraction for 316L(N) steel at 600°C.

On Figure 3, simulated rupture properties for intermediate tests (2, 3, 4 and 5) are consistent with experimental ones. The experimental "Monkman-Grant" constant [10] (time to rupture multiply by the minimal strain rate) represented on Figure 3, shows that the maximal creep strain first increases when strain rate is in the range 10^{-3} to 10^{-5}, and then decreases when strain rate is lower than 10^{-5}. This phenomenon can also be observed on the stress-rupture time curve with the slope variation for long rupture times. As observed on Figure 3, simulated creep rupture strain is in good agreement with experimental one. The use of a diffusion term in the model formulation enables to assess the loss of creep ductility observed for low strain rate levels (or long rupture times). On Figure 3, the Monkman-Grant constant derived from a Katchanov criterion, fitted on the stress-rupture time curve, is also plotted. As we can see, the dependence of creep ductility to strain rate can not be assessed with a single set of parameters for such criterion, when it is possible with a more physically based model as equation (1).

As mentioned above, the critical damaged fraction is not fitted, but computed as a result of equations (1) and (2) with optimal values of parameters $\mathbf{V_g}$ and **A.** To use the model for intergranular creep rupture under multi-axial stress states, no more fitted is needed, as the effect of triaxiality is explicitly defined in equations (1) and (2). On figure 4, a post processing estimation of the critical damaged fraction is computed and plotted versus equivalent stress and triaxiality levels. The critical damaged fraction sensitivity observed on figure 4 can be explained as following :

- softening rate will be enhanced by increasing triaxiality and equivalent stress,
- viscoplastic hardening curve slope will decrease under increasing equivalent stress.

CREEP RUPTURE ASSESSMENT ON NOTCHED SPECIMENS

In order to check the ability of the model to take into account constraint effect, creep rupture assessments on notched specimens are compared with experimental results. The latter are extracted from reference [2] and correspond to the two type of specimens presented on Figure 5. Mechanical fields, needed for intergranular creep damage integration, are computed with finite element models of Figure 5. The creep test is simulated using an elastoplastic behaviour for the first loading step, and a primary-secondary creep law for the dwell period. Computations are achieved using CAST3M the CEA finite element software. Simulated rupture curves are compared to experimental ones on Figure 5. On the latter, experimental results show an enhancement of creep rupture properties for notched specimens compared to smooth ones. This result is linked to a smaller equivalent stress in the minimal section of the notch specimen, because of a higher triaxiality ratio. As presented on Figure 5, simulated results give a best fit assessment of notch radius effect on creep rupture time.

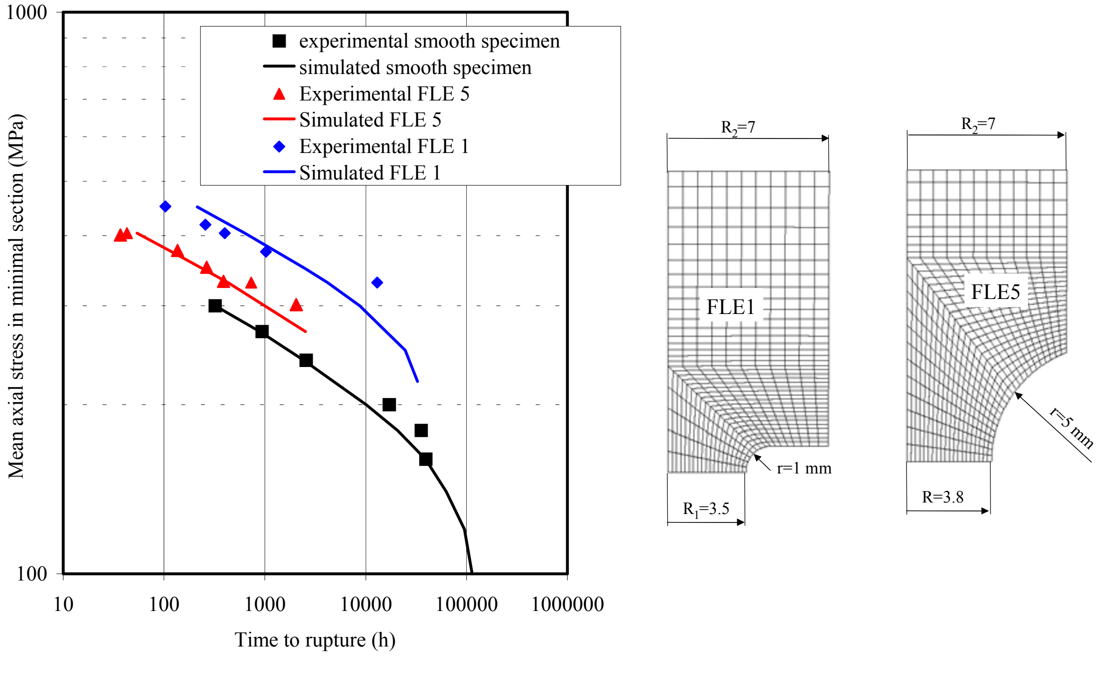

Figure 5 : Creep rupture curves for 316L(N) at 600°C on smooth and notch specimens.

CREEP CRACK INITIATION AND GROWTH ASSESSMENTS

The objective is to validate the proposed formulation for the simulation of creep crack initiation and growth from an initial defect. In this case, main difficulties are due to the stress-strain field singularity and the high triaxiality ratio at the crack tip. Experimental results on fatigue pre-cracked CT and axisymetric specimens are coming from reference [2]. Numerical simulation of creep crack initiation and growth is based on finite element computations, with an explicit coupling of constitutive and damage equations. The mesh characteristic size on the crack path is set at 0.05 mm. Crack growth is simulated with softening mechanical properties of cracked elements, where the damaged as reached its critical value.

Creep crack initiation times are simulated for three fatigue pre-cracked specimens of reference [2]. Main geometrical and loading characteristics are detailed on Figure 6 and Table 2. Mechanical fields computation is based on the same procedure as used for notched specimens. The finite element model has a refined mesh around crack tip, and crack initiation time is defined as the rupture of the first crack tip element. Simulated and experimental results are compared on Figure 6, where initiation time is plotted versus the C^*_{exp} parameter in a log-log (Ti-C*) graph. The parameter C^*_{exp} is computed using global load and load-line displacements values. As presented on Figure 6, simulated results are in a very good agreement with the experimental mean curve, with a relative error lower than 20% on initiation time. This error is very small when it is compared to the ratio of 5 between lower and upper bounds of experimental data of Figure 6. This second application shows that the uniaxial identification of the proposed model can also be extrapolated for creep rupture assessment under high triaxiality ratio and stress-strain singularities. The characteristic mesh size of 0.05 mm use in this study should be considered as a material parameter, intrinsic to geometry and loading.

Specimen	Material	Temperature	Load (KN)	Initial fatigue crack depth
AX13	316L(N)	600 °C	41.68	5.15 mm
AX15	316L(N)	600 °C	35.05	5.45 mm
CT62	316L(N)	600 °C	4.12	23.76 mm

Table 2:   Characteristics of creep crack initiation tests on fatigue pre-cracked specimens.

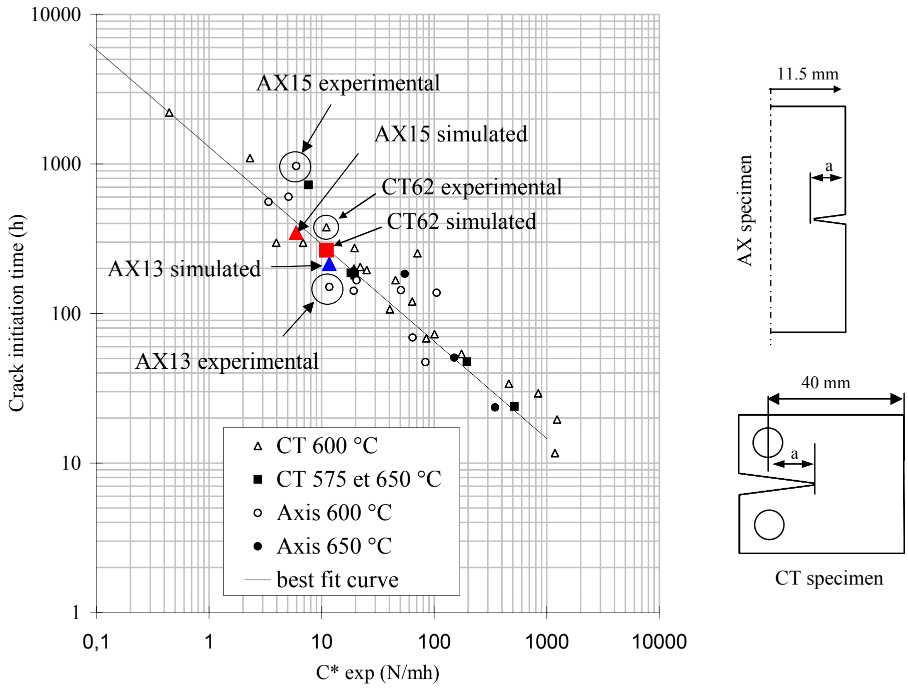

Figure 6 : Creep crack initiation time in fatigue pre-cracked specimens

On AX15 specimen used for crack initiation, the model is tested for creep crack growth assessment. Simulation procedure is the same than for crack initiation, with a continuous computation after the rupture of the first element. Numerical results are compared to experimental ones on figure 7. As presented on the latter, numerical assessment is in good agreement with experimental crack growth. Relative error on crack growth rate is lower than 25%.

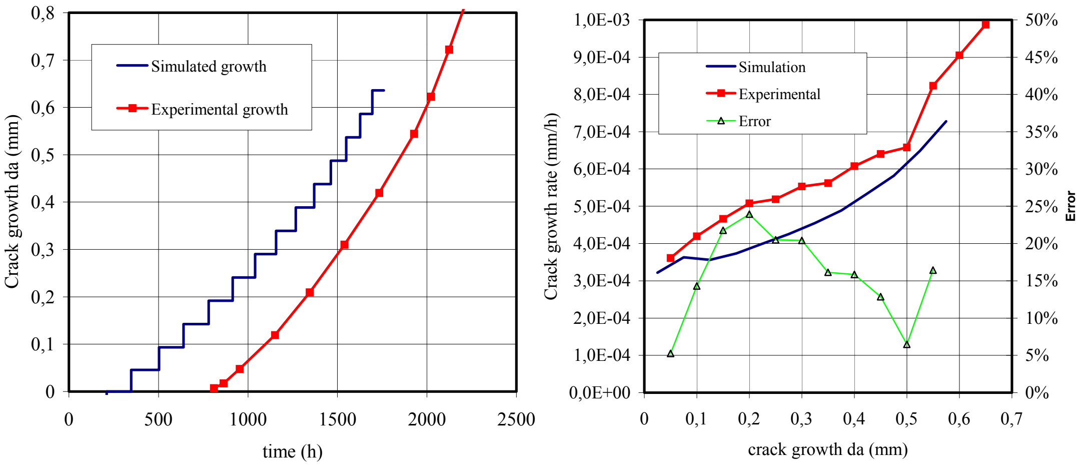

Figure 7 : Creep crack growth on AX15 specimen.

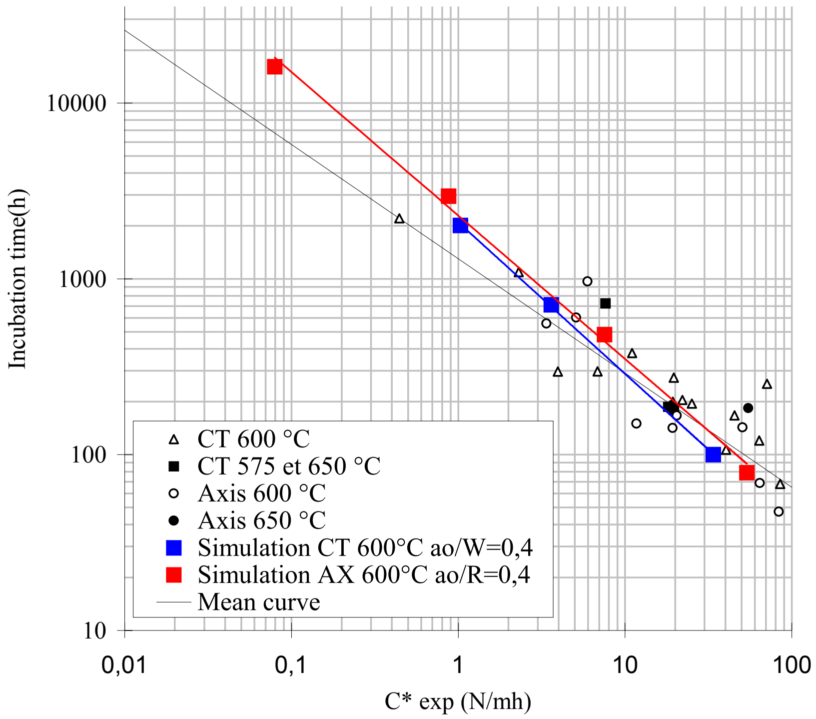

Figure 8 : Long time extrapolation of creep crack initiation assessment.

On figure 8, long time extrapolations of creep crack initiation assessment with the proposed model are compared with an extrapolation of the global criterion $\left(T_i.C^{*0.65} = 1300\right)$ fitted on experimental data. It is interesting to see that both assessments, based on very different formulations, are in a rather good agreement for long time extrapolation. This kind of result opens many perspectives to use numerical simulation, with a physically based model, to check the validity of a design global criterion when it is extrapolated outside the fitted domain. Of course, the capacity of the physically based model to be extrapolated has first to be demonstrated.

CONCLUSION

A new intergranular creep damage model has been proposed for high temperature life time assessments in austenitic steels. The model formulation is physically based and takes into account : intergranular voids nucleation, growth and coalescence. Nucleation is based on an empirical law where fraction void rate is proportional to the creep strain rate. Voids growth rate includes the contribution of viscoplastic strain rate of surrounding grains (Gurson) and vacancies diffusion along grain boundaries (Hull&Rimmer). Voids coalescence is based on a mechanical rupture criterion, where the competition between damage softening and viscoplastic hardening is considered.

The specificity of our approach is to use only two parameters to fit in the model and to introduce the constraint effect via a physically based formulation of void growth rate and intergranular rupture criterion. Then, a simple identification procedure has been proposed with the only results of uniaxial creep tensile tests.

Creep rupture assessments for notched specimens have been presented. The model can predict the effect of notch radius on rupture time. These results confirms the model validity when it is extrapolated on multiaxial stress states. Creep Crack initiation and growth assessments have also been proposed for fatigue pre-cracked CT and axisymetric specimens. Simulations are in good agreement with experimental results, with a relative error, on initiation time and crack growth rate, lower than 25% compared to mean experimental values. Model extrapolations, for long crack initiation times, are compared to the C* master curve extrapolations. Both assessments, based on very different formulations, are in a rather good agreement for long time extrapolations.

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