# AN ELASTO-VISCOPLASTIC MODEL COUPLED TO DAMAGE AND GRAIN GROWTH TO TAKE ACCOUNT OF MATERIAL VARIABILITY

Benoit Vereecke*, René Billardon**
*DEN/SAC/DM2S/SEMT/LM2S, CEA Saclay, 91191 Gif sur Yvette Cedex, France
**LMT Cachan, ENS-Cachan, Paris VI, CNRS, 61, Avenue du Président Wilson 94235 Cachan Cedex, France

## INRODUCTION

The final objective of this study is the prediction of the failure of nuclear structures at very high temperatures in accidental conditions taking account of the material variability. Other studies on mini structures [1] have compared the failure behaviour of French and German steels for pressure vessels.

The material used to build French reactor pressure vessels 16MND5 steel, shows at high temperature different damage mechanisms according to its origin : transgranular by growth and coalescence of cavities or intergranular. We can see on figure 1 that this phenomenon can lead to very different failure times during creep tests.

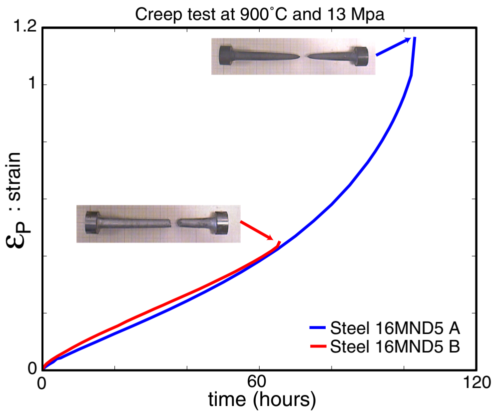


**Figure 1.** Failure time for 2 origins of 16MND5 steel with the same experimental conditions

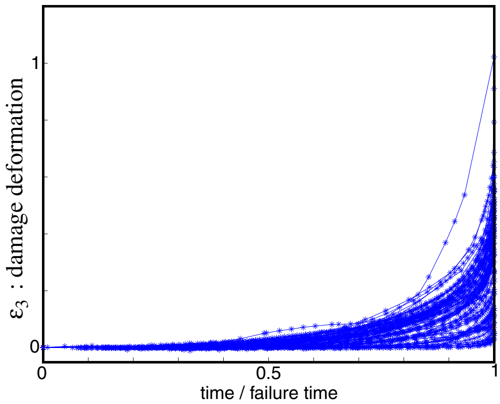


**Figure 2.** Random character of damage deformation

A statistical analysis of 61 creep tests [2], for 5 temperature levels (900 to 1300$^o$C) and 2 origins of 16MND5, showed that the damage threshold and damage evolution measured through the value of strain during tertiary creep (see figure 2), have a random character according to material origin and thermal history. The cause of these different damage evolutions has been seeked by metallurgical analyses. The metallurgical parameter that explains this random character has been identified and introduced in an elasto-viscoplastic constitutive law with isotropic hardening coupled to two damage evolution laws.

## METALLURGICAL STUDY

Different heat treatments have been performed on 16MND5 of two different origins in order to reproduce the thermal history applied to creep specimens before the mechanical load is applied.


**Figure 3.** Austenitic grain of steel A after 10h at 1000$^o$C ($\simeq$ 100-150 $\mu$m in diameter)


**Figure 4.** Austenitic grain of steel A after 10h at 1000$^o$C ($\simeq$ 200-300 $\mu$m in diameter)

We have noticed that for long enough austenitisation the austenitic grain size is different from one steel to another.

For an austenitisation of 10 hours at 1000$^o$C (see figures 3 and 4), we observed after chemical attack that the austenitic grain size of steel A is about twice smaller than the austenitic grain size for steel B. We observed the same result for austenitisations of 0.5 hours and 5 hours at 1100$^o$C.

For austenitisation at lower temperatures or for shorter times, the austenitic grain is difficult to observe. However, for steel A, we have been able to observe the same austenitic grain size than M. Martinez [3].

To conclude, it appears that the austenitic grain size is the important metallurgical parameter to differentiate damage mechanisms in 16MND5 of different origins, intergranular damage becoming predominant for smaller austenitic grain sizes.

## CONSTITUTIVE LAW

To describe these phenomena, we have chosen a macroscopic elasto-viscoplastic constitutive law with isotropic hardening coupled to two damage evolution laws [4] [5]. The limited complexity of such a macrocopic law is compatible with the cost of the numerical simulations of the ruin of industrial composants. However, we have taken account of the microstructural parameter viz. the austenitic grain size $d_\gamma$ that controls the evolution of intergranular damage $D_c$. We supposed that the evolution of transgranular damage $D_d$ is isotropic and not affected by this microstructural parameter. Conversely, we have considered that intergranular damage is anisotropic and dependent on austenitic grain size. Moreover, we have considered only one isotropic hardening $R$ since we want to simulate only the failure for monotonic loadings. The partition of strain is as follows:

$$\varepsilon = \varepsilon^{elas} + \varepsilon^{vplas} + \varepsilon^{th} \tag{1}$$

where $\varepsilon^{elas}$ stand for elastic strains, $\varepsilon^{vplas}$ for viscoplastic strains and $\varepsilon^{th}$ for strains due to thermal dilatation. We introduce both damages with damaged elasticity tensor as follows:

$$\varepsilon_{elas} = \tilde{E}^{-1}\left(D_c, D_d\right) : \sigma \quad \text{with} \quad \tilde{E}^{-1}\left(D_c, D_d\right) = \frac{1}{E(1-D_d)} \begin{bmatrix} \frac{1}{1-D_c} & -\nu & -\nu \\ -\nu & 1 & -\nu \\ -\nu & -\nu & 1 \end{bmatrix}_{\sigma_I, \sigma_{II}, \sigma_{III}} \tag{2}$$

where $\sigma_I \geq \sigma_{II} \geq \sigma_{III}$ stand for principal stresses, $E$ for Young's modulus and $\nu$ for Poisson's ratio. The threshold of viscoplasticity is as follows:

$$f_{vp} = \tilde{\sigma}_{eq} - R - \sigma_Y(d_\gamma) - K\dot{p}^{\frac{1}{n}} \quad \text{with} \quad R = Q(d_\gamma)\left(1 - e^{-bp}\right) \tag{3}$$

where $\sigma_Y, Q, b$ are material parameters that are dependent on temperature. The equivalent effective stress $\tilde{\sigma}_{eq}$ is obtained from the shear elastic energy. The law of normality and the generalized Norton's law are as follows:

$$\dot{\varepsilon}^{vplas} = \frac{3}{2}\dot{p}\frac{\partial\tilde{\sigma}_{eq}}{\partial\sigma} \quad \text{with} \quad \dot{p} = \left(\frac{\tilde{\sigma}_{eq} - R - \sigma_Y}{K}\right)^n \tag{4}$$

where $K, n$ are temperature dependent parameters material. The evolution of transgranular damage is given by Lemaitre's ductile law [4] as follows:

$$\dot{D}_d = \left(\frac{Y}{S}\right)^s \dot{p} \tag{5}$$

where $S, s$ are temperature dependent parameters material. The evolution of intergranular damage is defined by Kachanov's law as follows:

$$\dot{D}_c = \left(\frac{\sigma_I}{A(d_\gamma).(1-D_c)}\right)^r \tag{6}$$

where $A, r$ are temperature dependent parameters material. These laws have been implemented in French finite element code CAST3M [6]. Experiments are under way to identify this law and the evolution of both damage mechanisms.

## References


[1] H.-G. Willschütz and E. Altsadt and B.R. Sehgal and F.-P. Weiss: Simulation of creep tests with French or German RPV-steel and investigation of a RPV-support against failure. *Annals of NUCLEAR ENERGY* **1033**:1033–1063, 2003.

[2] B. Vereecke and R. Billardon: Analyse probabiliste du comportement en fluage du 16MND5. *Congrès Français de Mécanique Nice (France)* 2003.

[3] M. Martinez: Jonction 16MND5-Inconel-316LN par soudage diffusion, Elaboration et calcul des contraintes résiduelles de procédé. *Thèse de l'ENSMP 1999*

[4] J. Lemaitre and J.-L. Chaboche: Mechanics of solid materials. *Dunod 2nd edition* 2001.

[5] C. Petry: Caractérisation de l'endommagement du Narloy-Z en fluage *Rapport de stage de DEA S3M (Master degree), University Paris VI 2003*

[6] Cast3M: CEA finite element software, web site http://www-cast3m.cea.fr