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Modeling Creep Behaviour of Boiler Grade Steels - Application to Grade 92 Steel

E.Cini[a*], E.Desdoit[b], A.Villani[a,b], J.Besson[a]

[a]*Vallourec Research Aulnoye (VRA), 60, route de Leval - BP 20149, 59620 Aulnoye Aymeries, France*
[b]*MINES ParisTech, Centre des Matériaux - UMR CNRS 7633, BP 87 - 91003 EVRY Cedex, France*

Abstract

Power generation is now striving to improve the global efficiency of boiler plants, targeting 50% or higher. To accommodate the necessary increase in steam temperature, new materials may be developed and/or existing materials must be employed to their best. This is mandatory for the design of boiler components. One contribution by V&M in that direction is the setting up of numerical models for major boiler grades regarding their creep resistance. In coordination with Mines ParisTech, the first application has been made to Grade 92.The methodology is presented together with the first simulations. Typically, creep is modelled using two deformation mechanisms which correspond respectively to a low stress regime and a high stress regime. Damage is also taken into account. Calculations were carried out using ABAQUS ®. Numerical results are compared with a series of creep tests performed at Vallourec Research Aulnoye (VRA). Further development and applications of the model are finally discussed.

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Keywords: Creep; grade 92 steel;mechanical modelling; damage; finite element analysis (FEA)

1. Introduction

Power Generation is now facing a very difficult challenge. It is linked to an ever growing energy demand [1a], together with increasing tension about fuels supply. Regardless of the exact composition of the Energy-mix for each country, major improvements are expected for all technologies. In the case of thermal power plants, constraint is mainly two-fold: more stringent regulations that tend to reduce CO_2 and other green house gases emissions [1b], and improving global efficiency in electricity production. The objective is set at 50% or higher. Thermodynamics gives no other option than to increase steam temperature, along with pressure, but this may require the development of (possibly new) compatible materials. If one relies on materials that are already available, development is still necessary for forming and testing components in said corresponding materials. New designs must also be proven. Programs for Advanced Ultra-Super Critical (A-USC) boilers were launched

* Corresponding author:
E-mail address: emmanuel.cini@vallourec.fr

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in Europe in the 90's for demo-plants expected by 2020 [2]. Programs for A-USC have also been recently launched in Asia where it now seems likely to see the first erection of an A-USC plant, maybe as soon as 2017 [3]. V&M is already engaged in these developments and is leading several research programs either internally or through collaborations [4,5].On a shorter term, overall efficiency may also be improved by optimizing each boiler component, that is, by using existing materials to their best. Doing so requires a precise and detailed knowledge of materials behaviour in terms of creep and oxidation/corrosion resistance. V&M is also active in that direction through support to its customers with the experience and expertise it has acquired in Powergen. More precisely, V&M has initiated a program aiming at providing numerical models for major boiler grades regarding their creep resistance.

This approach appears as an efficient way to identify the expectations of the customers in terms of component design or life-time assessment. They provide a formal basis for tackling these problems. It is a matter of fact that maintenance is a growing issue as plants are getting older, worldwide. First application has been made to Grade 92 [6], in a two steps collaboration with Mines ParisTech.

2. Creep modeling

2.1. Preliminary work

2.1.1. Metallurgical observations

The first step consisted in a detailed analysis of the microstructure evolution of Grade 92 upon creeping. This was done through the PhD work performed by C. Panait [7], funded by V&M and conducted at Mines ParisTech. Maximum rupture times for observed samples reached nearly 50.000 h and 34.000 h at 600°C and 650°C respectively.

The number density of MX carbo-nitride (M=Vanadium, Niobium) remained nearly stable while the $M_{23}C_6$ Chromium carbides got enriched in Iron but grew moderately in size.

More clearly, sub-structure coarsening and matrix recovery could be evidenced. Laves phases precipitation and growth appeared as the most noticeable phenomenon. Creep damage also developed during long-term tests.

2.1.2. Mechanical approach: stress splitting and simplifying assumptions

Using a simple Norton flow rule, two creep regimes were evidenced; a High Stress (Hs) and a Low Stress (Ls) regime, with threshold values around 160 MPa and 110 MPa respectively for 600°C and 650°C [7]. This legitimated the use of a stress splitting model, like the one previously developed by Gaffard and Besson at Mines ParisTech [8, 9].

To keep such a model as simple as possible, only the Laves phases fraction was added as an internal variable to mimic the microstrusture evolution with time. In the same way, deformation mechanisms were supposed to have only additive contributions to strain. The only explicit coupling with damage nucleation is restricted to the low stress regime.

2.2. Mechanical model

As a result, the corresponding material model stipulates that three mechanisms contribute to the permanent creep deformation. The quasi plastic (qp) mechanism is active during loading and final rupture while the high stress (Hs) mechanism is preponderant during short term creep tests and the low stress (Ls) mechanism mainly contributes to long term creep test.

The strain rate tensor is then expressed as:

$$\underline{\dot{\varepsilon}} = \underline{\dot{\varepsilon}}_e + \underline{\dot{\varepsilon}}_{qp} + \underline{\dot{\varepsilon}}_{Hs} + \underline{\dot{\varepsilon}}_{Ls} \qquad (1)$$

where the first term corresponds to the elastic reversible deformations and is given by the Hooke's law.

Each viscoplastic mechanism is then based on a potential defined for m = qp, Hs and Ls as:

$$\phi_m = \sigma_m^* - R_m \tag{2}$$

σ_m^* is a scalar effective stress which takes into account damage using the Gurson-Tvergaard-Needleman approach [8, 9].

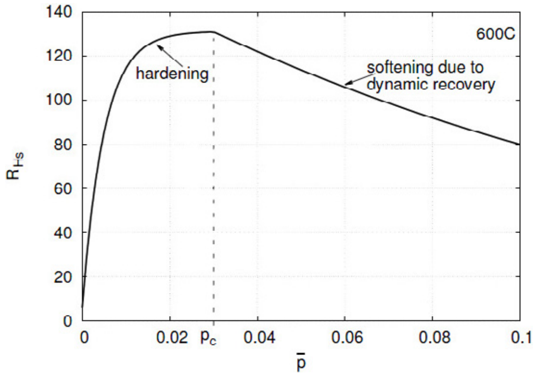

Fig. 1. Softening is introduced for the flow stress in the high stress mechanism. $\bar{p}$ is the cumulated irreversible strain.

R_m is the flow stress triggering the corresponding mechanism. It is constant for both qp and Ls but depends on the cumulated irreversible strain for Hs in order to take into account softening due to dynamic recovery as shown in Fig. 1.

The strain rate for each mechanism is then obtained through a normality rule:

$$\dot{\underline{\epsilon}}_m = (1-f)\dot{p_m}\frac{\partial \phi_m}{\partial \underline{\sigma}} \tag{3}$$

where f represents the total damage variable. $\dot{p}_m$ is the plastic multiplier which is homogeneous with a plastic strain rate. It is calculated using a standard Norton law for m = qp and Ls and a modified Norton law for m = Hs:

$$\dot{\rho}_m = K_m \langle \frac{\phi_m}{\sigma_{0m}} \rangle^{n_m} \tag{4a}$$

$$\dot{\rho}_{Hs} = K_{Hs}(1+a) \langle \frac{\phi_m}{\sigma_{0m}} \rangle^{n_m} \tag{4b}$$

The quantity a used for the Hs mechanism is proportional to the amount of precipitated Laves phases in the alloy. This accounts for the acceleration of creep rate noticed for pre-aged specimens at 600 and 650°C, which however, saturates after 10000 hours of exposure. K_m, σ_{0m} and n_m are material constants.

Damage is partitioned in the same way as strain, so that contributions from each viscoplastic mechanisms write:

$$\begin{aligned} \dot{f}_{QP} &= (1-f)tr(\dot{\underline{\epsilon}}_{QP}) \\ \dot{f}_{LS} &= (1-f)tr(\dot{\underline{\epsilon}}_{LS}) + (A_{LS} + B_{LS}(\tau - 1/3))\dot{p}_{LS} \\ \dot{f}_{HS} &= (1-f)tr(\dot{\underline{\epsilon}}_{HS}) \end{aligned} \tag{5}$$

In this approach, nucleation, that is, the formation of voids, is supposed to be exclusively caused by the Ls mechanism in areas where the stress triaxiality τ is high (see 5b). A_{Ls} and B_{Ls} are material constants. Once formed, these voids grow through all three deformation mechanisms.

2.3. Implementation

After completion of the PhD work [7], the second step of the collaboration with Mines ParisTech consisted in the implementation of the mechanical model on V&M computers. This was done at VRA, in the commercial code ABAQUS® using a CREEP user subroutine. Hence, all the simulations presented hereafter were run with ABAQUS® Standard version 6.9-1.

3. Preliminary results

Here are only shown preliminary simulations at 600°C, with main focus on high stress creep tests which provide fast results. These results were obtained using the set of parameters identified in [7].

3.1. Standard creep samples

The model is applied to a conventional creep configuration where smooth cylindrical samples are submitted to constant loads. Typical dimensions are given in [7]. In this configuration, the stress state is uniaxial and homogeneous and the calculated rupture times and predicted strains are in fairly good agreement with the experimental results as shown in Fig. 2 for three conditions of stress at 600°C.

One of the hypotheses of the model is that a high triaxility ratio induces a faster development of the creep damage. However with smooth creep samples, it is not possible to validate this effect as the uniaxial stress state implies a constant triaxiality equal to 1/3 throughout the sample and during the most part of the test. Stress localization by necking leading to higher levels of triaxiality only occurs at the very last stage preceding rupture, see Fig. 3.

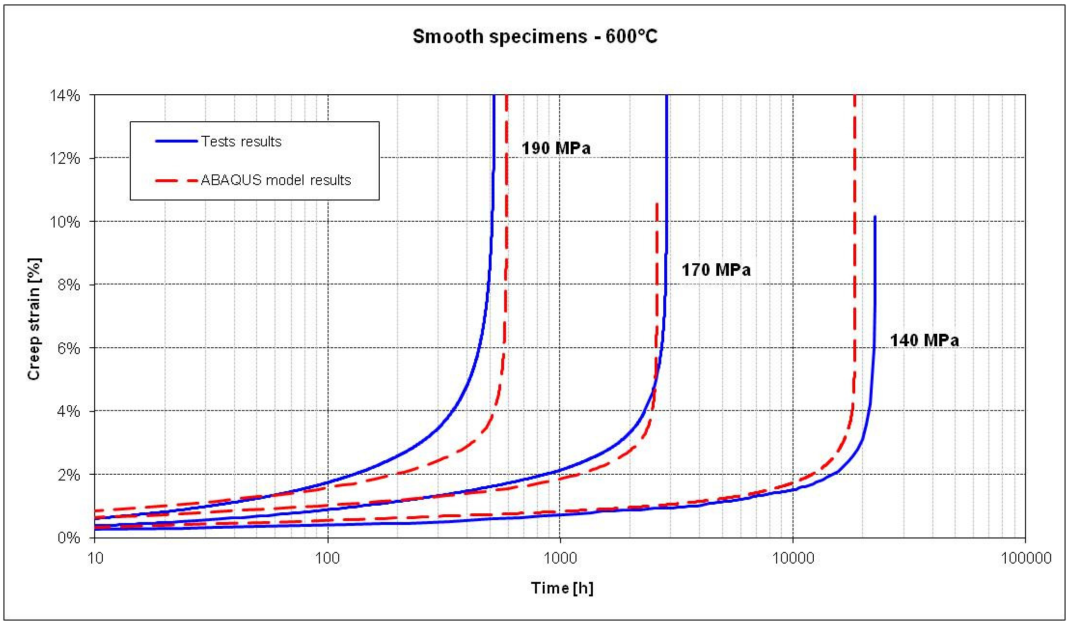

Fig. 2. Numerical simulations agree fairly well with experimental results for smooth samples.

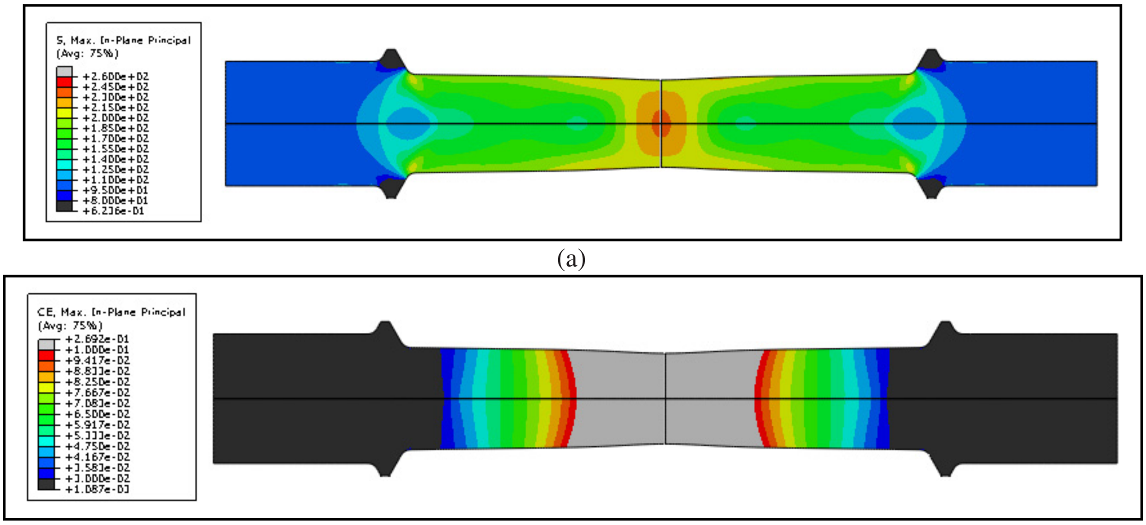

Fig. 3.Stress heterogeneity (triaxiality) a) and necking b) only develop just before rupture for smooth creep samples (170 MPa-600°C).

3.2. Notched samples

Using samples with various notch geometries, such as the one depicted in Fig. 4, is a practical way to address the effect of triaxiality. More precisely, the evolution of stress field and damage can be monitored during the test.

Figure 5 shows the initial distributions of axial stress and triaxiality ratio in the notched section of the sample. Damage first appears at the surface together with the initial creep strains that are induced by the higher axial stresses.

However, it subsequently develops faster towards the centre of the samples where triaxiality is maximum, see Fig. 6.

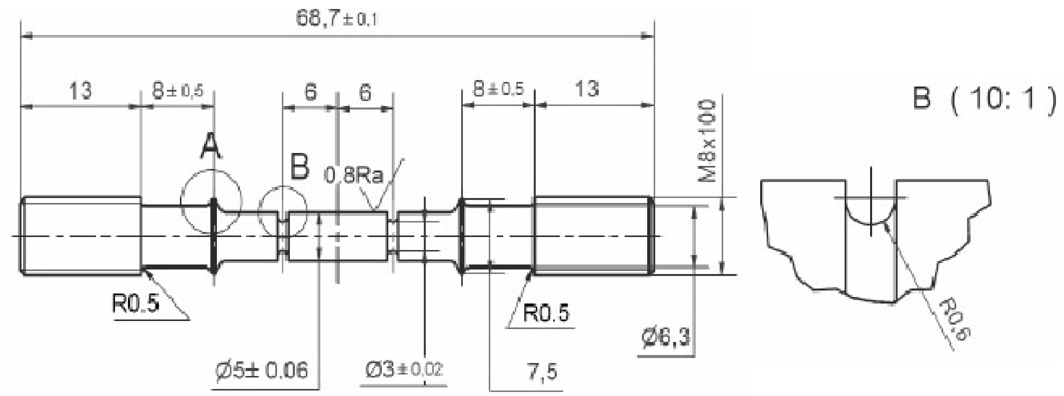

Fig. 4. Dimensions (mm) of notched creep samples (NTCD0.6M).

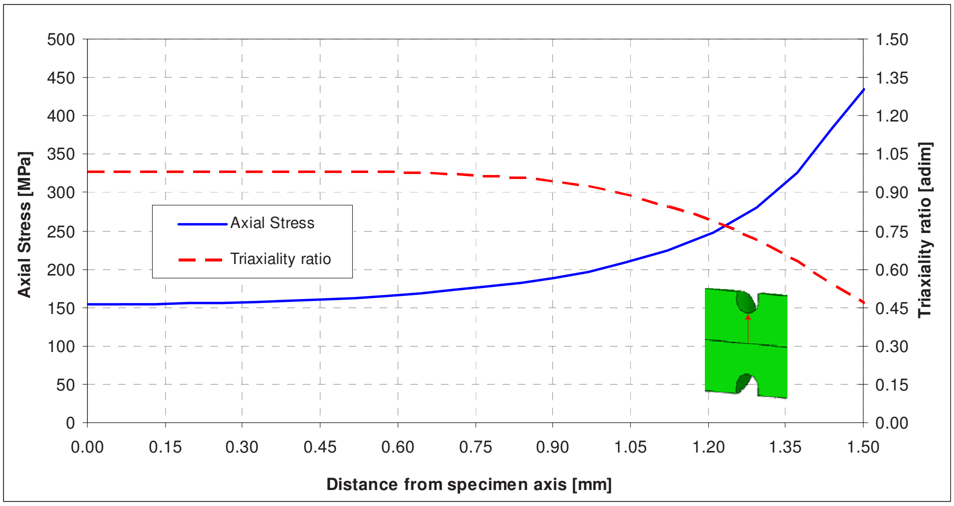

Fig. 5. Initial distribution of axial stress and triaxiality ratio from sample axis to notch bottom for notched sample NTCD0.6M under 240 MPa at 600°C.

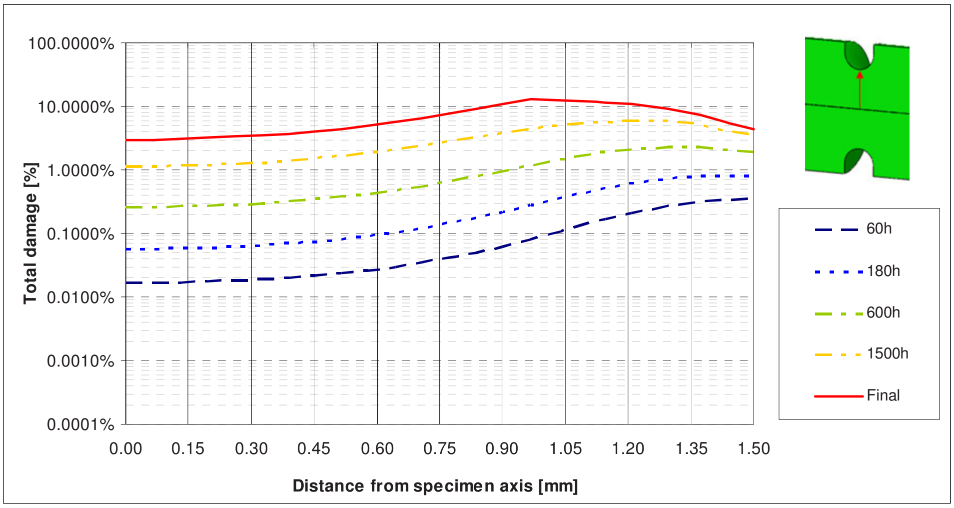

Fig. 6.Progressive development of the creep damage towards the centre of the sample during the test notched sample NTCD0.6M under 240 MPa at 600°C.

The interest of such an analysis is that the position of the maximum damage in the simulation can be checked against metallographic observations of the crept samples. Such comparisons were done in [7] for a series of notched geometries to validate the tendencies predicted by the model.

The above behaviour also highlights that the interactions between stress, strain and damage are much more complex with notched samples than with conventional uniaxial tests. As a matter of fact, the current model does not reproduce the total elongation of notched samples as exactly as that of smooth samples.

4. Conclusion and perspectives

V&M has initiated a program for modeling the creep behaviour of Boiler grades. First application has been made on Grade 92. Following a preliminary PhD work conducted at Mines ParisTech., a mechanical model has been implemented at Vallourec Research Aulnoye (VRA).

This numerical tool proved very useful to analyse and better understand the creep behaviour in complex conditions. The current set of parameters used for the model provides fairly good results for smooth samples for both creep elongation and rupture times. The correlation is not as good for notched samples even though the tendencies regarding the development of damage are consistent with experimental observations.

V&M keeps working on this mechanical approach, by considering either refining the parameters used for the current model or modifying the model formulation.

In the future, practical benefits could be found in the design of new creep tests for screening purposes. Another potential application could be to simulate boiler components in order to identify where damage is likely to initiate and develop. This could be a useful guiding line for Utilities during on site inspections. For V&M, this could also be an efficient way to help and accompany its customers.

Acknowledgment

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