Cyclic behaviour modelling of martensitic hot work tool steels

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CYCLIC BEHAVIOUR MODELLING OF MARTENSITIC HOT WORK TOOL STEELS

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ABSTRACT

In this paper, an unified elasto-viscoplastic behaviour model based on internal states variables, is investigated in order to describe the thermo-mechanical stress-strain fatigue response of tempered martensitic steels. This model includes an isotropic part (drag stress) describing the cyclic softening of martensitic steels. The memory effect is introduced to take into account the influence of the plastic strain range on the amount of the cyclic softening. The kinematic part (back stress) of the model allows the description of complex load conditions to which tool steels are subjected. Thus, strain recovery (Baushinger effect) and time recovery terms (cyclic behaviour including tensile and compressive dwell time and ratcheting) are considered. Moreover, the identification methodology of the model parameters from only two sets of experimental data is presented; the coefficients of the kinematic and isotropic parts are determined successively. The main difficulty consists in reaching a good description both of the cyclic behaviour for different strain rates and the ratcheting effect.

KEYWORDS

Tempered martensitic steels, stress-strain modelling, constitutive model identification, numerical simulation.

INTRODUCTION

Martensitic tool steels are used in forming processes like forging or extrusion for their good mechanical strength at high temperature combined with sufficient ductility. They undergo thermo-mechanical cyclic loads which are very hard to evaluate from an experimental point of view and whose levels strongly depend on the location on the structure. So, numerical simulation seems to be a significant way to reach this information in order to optimize the tools design and improve their lifetime.

Thus, a good understanding of the martensitic steel behaviour is necessary. The heat treatment to which they are subjected consists in annealing, austenitizing followed by a quenching and one or two tempering operations. This treatment leads to a complex microstructure [1]. The quench stage changes the austenite into martensite and the tempering (560°C) gives more ductility to the material [2]. At the end, the microstructure is composed of thin lathes where the dislocation density generated during the quench associated with carbides precipitation occurring during the tempering makes the microstructural investigation difficult.

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Besides the microstructural aspect, the different kinds of loads induced by the forming process itself have an influence on the behaviour. Thus, in this work, a cyclic constitutive behaviour model adapted to martensitic steels and industrial forming conditions is investigated in the framework of the thermodynamics of irreversible processes.

EXPERIMENTAL BEHAVIOUR AND MODELLING

Fatigue experimental behaviour of martensitic steels

The 42 HRC (Rockwell hardness) 55NiCrMoV7 martensitic steel is investigated in isothermal fatigue conditions for a temperature range between 20 and 500° C.
The continuous softening from the first cycle until rupture is typical of such materials. If the semi-stress amplitude is represented versus the number of cycles, this softening can be divided in three successive stages (see Figure 1).

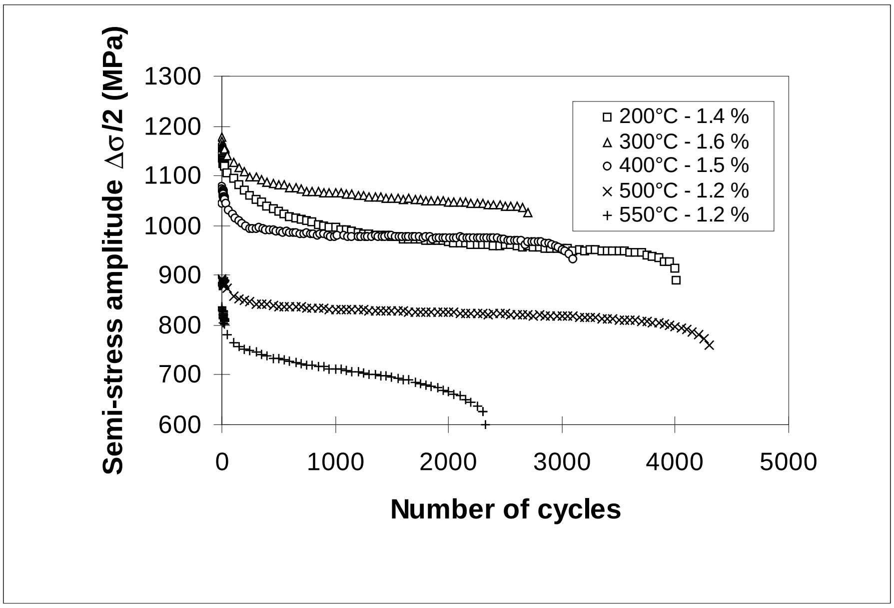

Fig. 1: Softening stages of the 55NiCrMoV7 martensitic steel [3]

Indeed, the strong softening stage occurring during the first hundred cycles is followed by a pseudo-stability one (weak softening) during the largest part of the tool life. At last, crack propagation occurs, defined by a fast decrease of the stress amplitude before the rupture [2].

Constitutive model selection

Selection of a constitutive model has to take into account the specificity of the tempered martensitic steel behaviour as well as the load paths during the forming process.

First, the fast evolutions during each inelastic transient can be described through kinematic variables (back stresses); the slow evolutions during the successive cycles corresponding to the cyclic softening of the material may be reproduced through an isotropic hardening variable (drag stress) [4].

Second, model has to reproduce material response under fatigue-relaxation loads and structure effects, which induce non-symmetrical stress-controled loads leading to ratcheting effects. This requires in general a more complex formulation of the kinematic hardening.

During the last years, several models have been formulated for such goals. The Armstrong & Frederick modelling introduces an evanescent memory term called dynamic recovery or strain recovery, which corresponds to a time independent recovery effect of the structure and simply describes an instantaneous recall effect. To take into account the dwell time and ratcheting effect, several methods have been followed: one of them implies a modification of the dynamic recovery term introducing a threshold stress [5], another one defines two stress states leading to two strain mechanisms and creating interactions between the different hardening variables [6].

In this work, a static recovery term is added in the kinematic hardening variable [7]. It is completely time-dependent and describes a slow recovery of the steel crystalline structure which occurs at high temperature by annihilation of dislocations and relaxation of internal stresses. Moreover, as the ratcheting strain is over-estimated, a third kinematic variable is introduced [8]. At last, all the strain levels reached during the different tests may be described by the three kinematic variables.

Slow cyclic softening is described through a drag stress including two terms, which describe the two different softening rates of the material [1]. At last, the influence of the plastic strain level on this softening range is taken into account through an asymptotic term of the isotropic variable [9].

Model formulation

Model formulation is based on the thermodynamics of irreversible processes; it is defined from two potentials, the free energy Ψ and the dissipation potential Ω.

Free energy formulation Ψ defining the associated variables. It is divided into an elastic and viscoplastic part [2].

$$\rho\Psi = \rho\Psi_{el} + \rho\Psi_{vp}\,; \qquad \rho\Psi_{el} = \frac{1}{2}\underline{\underline{A}}\underline{\varepsilon_{el}} : \underline{\varepsilon_{el}}; \qquad \underline{\underline{A}} \text{ is the elastic stiffness tensor}$$

$$\rho\Psi_{vp} = \frac{1}{3}\sum_{i=1}^{3} C_i \underline{\alpha_i} : \underline{\alpha_i} + \frac{1}{2}Q_1 r_1^2 + \frac{1}{2}bQ_2 r_2^2$$

Thus, state laws can be written:

$$\underline{\sigma} = \underline{\underline{A}}\underline{\varepsilon_{el}}; \qquad \underline{X_i} = \frac{2}{3}C_i \underline{\alpha_i}; \qquad i = 1,2,3; \qquad R_1 = Q_1 r_1; \qquad R_2 = bQ_2 r_2\,; \qquad (1)$$

$\underline{\sigma}$ defines the stress state and $\underline{\varepsilon_{vp}}$ the viscoplastic strain.

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[2] Note: $\underline{\underline{T}}$ the fourth order tensors and $\underline{T}$ the second order tensors.

$$\underline{T} : \underline{T} = \sum_{i,j=1}^{3} \underline{T_{ij}}^{\,2}$$

$\underline{X}_i$ defines the kinematic stress of the hardening and R_i the isotropic one. They are respectively the associated variables to the internal ones $\underline{\alpha}_i$ and r_i. Q_i, C_i and b are material and temperature-dependent parameters.

Dissipation potential Ω *defining the internal variables.* It is divided in two components. Ω_{vp} is the viscoplastic potential, defined as a function of the yield surface f and Ω_R is the recovery potential.

$\langle u \rangle = uH(u)$ with H the Heavyside function.

$$\Omega = \Omega_{vp}(f) + \Omega_R; \quad \Omega_{vp}(f) = \frac{K}{n+1}\left\langle \frac{f}{K} \right\rangle^{n+1}; \quad f = J\left(\underline{\sigma} - \sum_{i=1}^{3} \underline{X}_i\right) - R_1 - R_2 - R_0; \quad (2)$$

with: $J(\underline{\sigma}) = \sqrt{\frac{3}{2}\underline{\sigma}' : \underline{\sigma}'}$; $\underline{\sigma}'$ is the deviatoric part of $\underline{\sigma}$.

$$\Omega_R = \sum_{i=1}^{2} \frac{M_i}{m_i + 1}\left\langle \frac{J(\underline{X}_i)}{M_i} \right\rangle^{m_i+1}$$

R_0 defines the initial elastic limit of the material, K, n, m_i and M_i are material and temperature-dependent parameters.

As a consequence, evolution equations of the internal variables can be written:

$$\dot{p} = \left\langle \frac{f}{K} \right\rangle^{n}; \quad \underline{\dot{\varepsilon}}_{vp} = \sqrt{\frac{3}{2}}\dot{p}\underline{n}; \quad \underline{\dot{\alpha}}_i = \underline{\dot{\varepsilon}}_{vp} - \frac{3}{2}\dot{p}\frac{D_i}{C_i}\underline{X}_i - \frac{3}{2}\frac{\underline{X}_i}{J(\underline{X}_i)}\left\langle \frac{J(\underline{X}_i)}{M_i} \right\rangle^{m_i}; \quad i = 1,2;$$

$$\underline{\dot{\alpha}}_3 = \underline{\dot{\varepsilon}}_{vp}; \quad \dot{r}_1 = \dot{p}; \quad \dot{r}_2 = \dot{p}(1 - br_2) \quad (3)$$

where $\underline{n}$ is the unit normal to the yield surface $f = 0$, which defines the elastic domain $(f < 0)$ and p the cumulated plastic strain.

We have: $\underline{n} = \dfrac{\partial f / \partial \underline{\sigma}}{|\partial f / \partial \underline{\sigma}|}$; $|\underline{n}| = 1$.

$\dot{p}$ is the cumulated plastic strain rate, which can be written: $\dot{p} = \sqrt{\frac{2}{3}\underline{\dot{\varepsilon}}_{vp} : \underline{\dot{\varepsilon}}_{vp}}$

The memory effect is written as usual; evolution rules for q and $\underline{\xi}$ are:

$$F = J(\underline{\varepsilon}_{vp} - \underline{\xi}) - q; \quad \dot{q} = \eta H(F)\langle \underline{n} : \underline{n}^* \rangle \dot{p}; \quad \underline{\dot{\xi}} = \sqrt{\frac{3}{2}}(1-\eta)H(F)\langle \underline{n} : \underline{n}^* \rangle \underline{n}^* \dot{p}; \quad (4)$$

where $\underline{n}^*$ is the unit normal to the memory surface $F = 0$.

So, we have: $\underline{n}^* = \dfrac{\partial F / \partial \underline{\varepsilon}_p}{\left| \partial F / \partial \underline{\varepsilon}_p \right|}$; $\quad \underline{\left| n^* \right|} = 1$

The parameter η induces a progressive memorisation.

The influence of this effect on the material softening is translated through the asymptotic value of the isotropic hardening variable:

$$Q_2(q) = Q_0 + Q_\infty e^{-2\mu q}$$

Note that the positivity of the intrinsic dissipation D verifies the thermodynamic principles:

$$D = \underline{\sigma} : \underline{\dot{\varepsilon}}_{vp} - \sum_i \underline{A_i} : \underline{\dot{I}_i}$$

$\underline{A_i}$ and $\underline{I_i}$ represent the associated and internal variables.

Finally, we get:

$$D = f.\dot{p} + \dot{p}\left(R_0 + \frac{R_2^2}{Q_2} + \sum_{i=1}^{2} \left(\frac{D_i}{C_i} J\left(\underline{X_i}\right)^2 + \left\langle \frac{J\left(\underline{X_i}\right)}{M_i} \right\rangle^{m_i} J\left(\underline{X_i}\right) \right) \right) \geq 0$$

Thus, the complete formulation requires the identification of 19 coefficients.

One-dimensional model formulation. Parameters of the three-dimensional model developed previously have been determined from push-pull tests, so it is necessary to write the formulation in that case.

The expression of the yield surface is then given by (2) : $f = \left| \sigma - \sum_{i=1}^{3} X_i \right| - R_2 - R_1 - R_0 \qquad (5)$

The equations (1), giving the expression of the state laws, can be written in the one-dimensional case:

$$\sigma = E\varepsilon_{el} \qquad X_i = C_i\alpha_i; \qquad i = 1,2,3; \qquad R_1 = Q_1 r_1; \qquad R_2 = bQ_2 r_2; \qquad (6)$$

E represents the Young modulus.

Moreover, the equations (3), providing the internal variables evolution, are given by:

$$\dot{p} = |\dot{\varepsilon}_{vp}| \qquad \dot{\varepsilon}_{vp} = sign\left(\sigma - \sum_{i=1}^{3} X_i\right)\dot{p}; \qquad \dot{\alpha}_i = \dot{\varepsilon}_{vp} - \frac{D_i}{C_i} X_i \dot{p} - \frac{|X_i|^{m_i - 1}}{M_i^{m_i}} X_i; \qquad i = 1,2;$$

$$\dot{\alpha}_3 = \dot{\varepsilon}_{vp}; \qquad \dot{r}_1 = \dot{p}; \qquad \dot{r}_2 = \dot{p}(1 - br_2); \tag{7}$$

The expression of the asymptotic value of the isotropic hardening is always given by:

$$Q_2(q) = Q_0 + Q_\infty e^{-2\mu q}$$

At last, the memory effect, given by (4), is expressed by:

$$F = |\varepsilon_{vp} - \xi| - q; \qquad \dot{q} = \eta \dot{p}\left\langle sign\left(\left(\sigma - \sum_{i=1}^{3} X\right)(\varepsilon_{vp} - \xi)\right)\right\rangle$$

$$\dot{\xi} = (1 - \eta)\dot{p}\left\langle sign\left(\left(\sigma - \sum_{i=1}^{3} X_i\right)(\varepsilon_{vp} - \xi)\right)\right\rangle sign(\varepsilon_{vp} - \xi) \tag{8}$$

EXPERIMENTAL TEST DECRIPTION

Two types of fatigue tests are performed on a 55NiCrMoV7 tool steel (42 HRC hardness) for the temperatures 20, 300, 400 and 500° C.

The first one (see Figure 2 and Figure 3) may be divided in two different steps:

- the first step is a symmetrical total strain controled push-pull low cycle fatigue test, with a fixed strain amplitude $\Delta\varepsilon_t$=1.6 %, itself divided in three substeps.
  - Substep 1 consists in a number of fatigue cycles so as to reach a cumulated plastic strain of 4 at a constant strain rate of $10^{-2}s^{-1}$.
  - During the substep 2, strain rate is varied from 10^{-2} to 10^{-3} and 10^{-4} s^{-1}; and three cycles are performed at each strain rate.
  - At last, fatigue-relaxation cycles are included with a strain rate of 10^{-2} s^{-1} and where relaxation-time is varied from 30 s (3 cycles) to 90 s and 600 s (2 cycles for each one).
- the second step consists in a non-symmetrical stress controled fatigue test at a constant stress rate of 100 MPa.s^{-1}. Ten cycles are performed.

The second test (Figure 4) consists in a symmetrical total strain fatigue test at constant strain rate 10^{-2} s^{-1}, in which strain amplitude is varied from ± 0.6, to ± 0.7, ± 0.8 and ± 0.9 before coming back to ± 0.7 %. The number of cycle for each strain amplitude is selected so as to reach a cumulated plastic strain of 1 during the number of cycles performed at each strain amplitude.

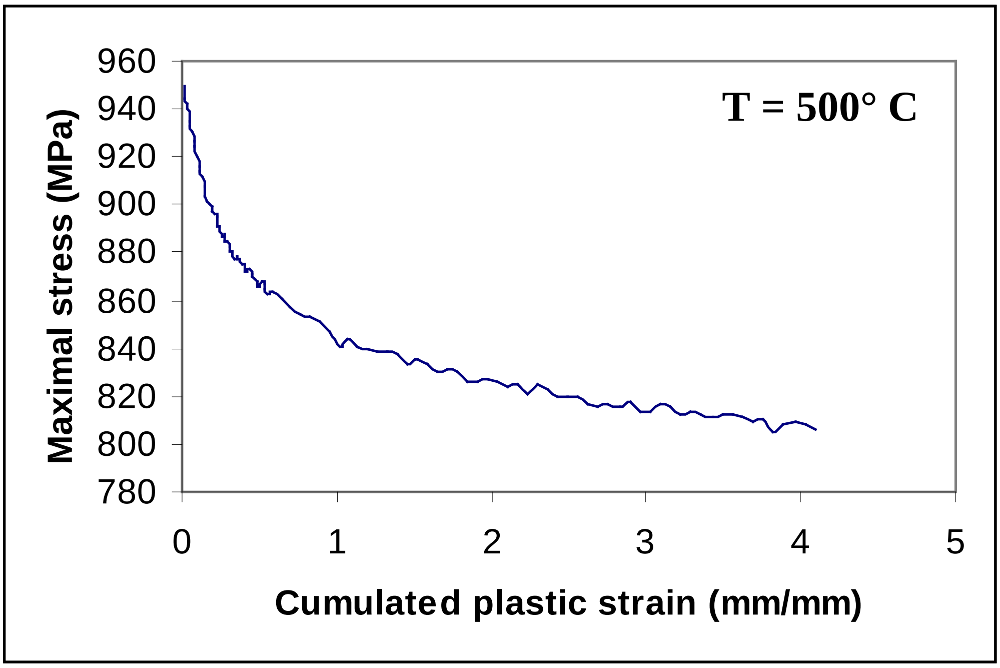

Fig. 2 : Experimental continuous softening (step 1, substep 1)

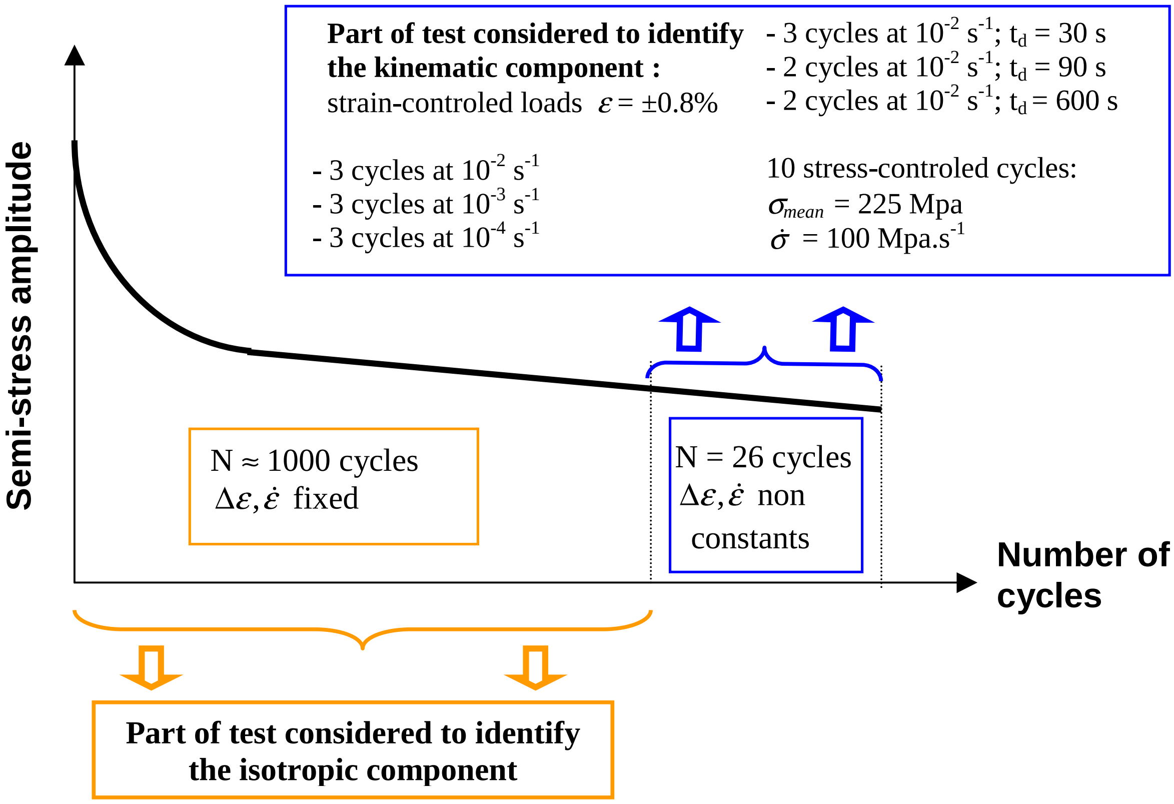

Fig. 3: Identification process

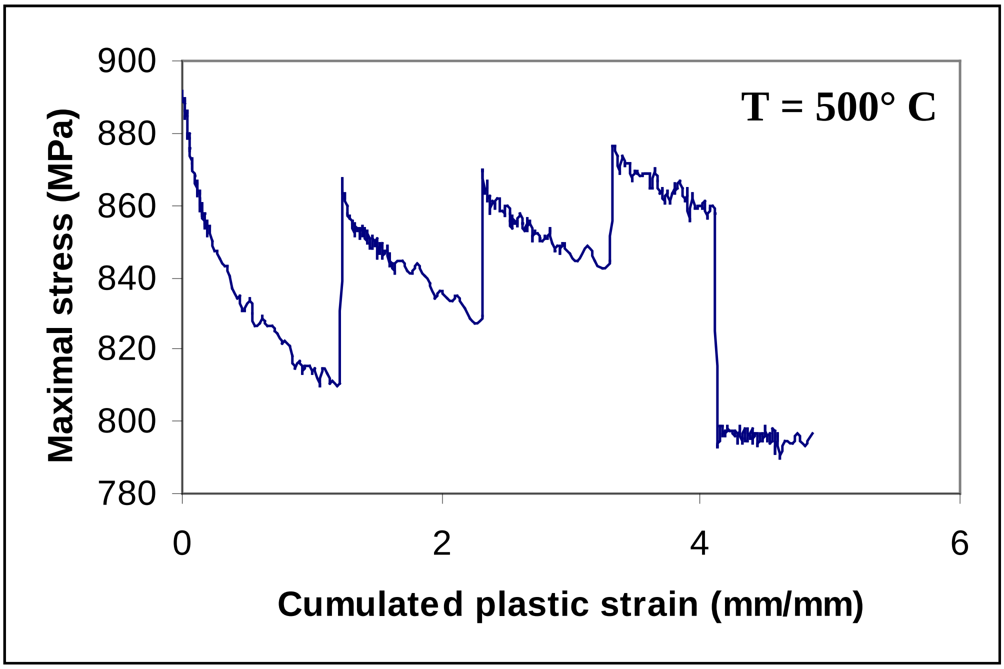

Fig. 4 : Experimental softening with different strain amplitude levels

MODEL PARAMETER IDENTIFICATION

The parameter identification of the behaviour model is presently performed with the SiDoLo software [10]. The yield surface (5), the state laws (6), the evolution equations (7) and the memory effect (8) are written on a one-dimensional form for the identification stage.

Identification is performed in two successive stages:

- kinematic and viscous parameter identification is completely performed with results of the first type of test (excluding substep 1). Knowing that during optimisation processes many local minima may be reached, a progressive process was implemented. First, results of the substep 2 are used to get an approximation of the viscous parameters. Then, substep 3 results are included to get a first level of the kinematic parameters (strain and time recovery); at this time, viscous parameters are constrained. At last, stress controled test are included to get the final set of values especially those for the second and the third kinematic strain recovery variables, which have a significant impact on ratcheting strain. At this point, the elasticity limit is an apparent value corresponding to the stabilised material.

- isotropic parameter identification is performed assuming all kinematic and viscous parameters determined previously fixed. Results of substep 1 of test 1 and test 2 are taken into account. The usefulness of test 2 is related to the strain memory parameters indentification which requires softening information for various plastic strain amplitudes.

Thus, two different tests are sufficient (one sample per test) to determine completely all the coefficients defined in the model formulation. At the end of this process, one set of parameters is determined for each temperature.

As shown in the following figures for a temperature of 500° C, such a progressive process allows to determine a set of parameters which gives a good fitting of experimental results. Figures 5, 6 and 7 simulations take mainly into account the viscous and kinematic parameters; whereas figure 8 shows that the isotropic variable allows a good agreement between simulated and experimental softening. Similar results were obtained for the other temperatures investigated.

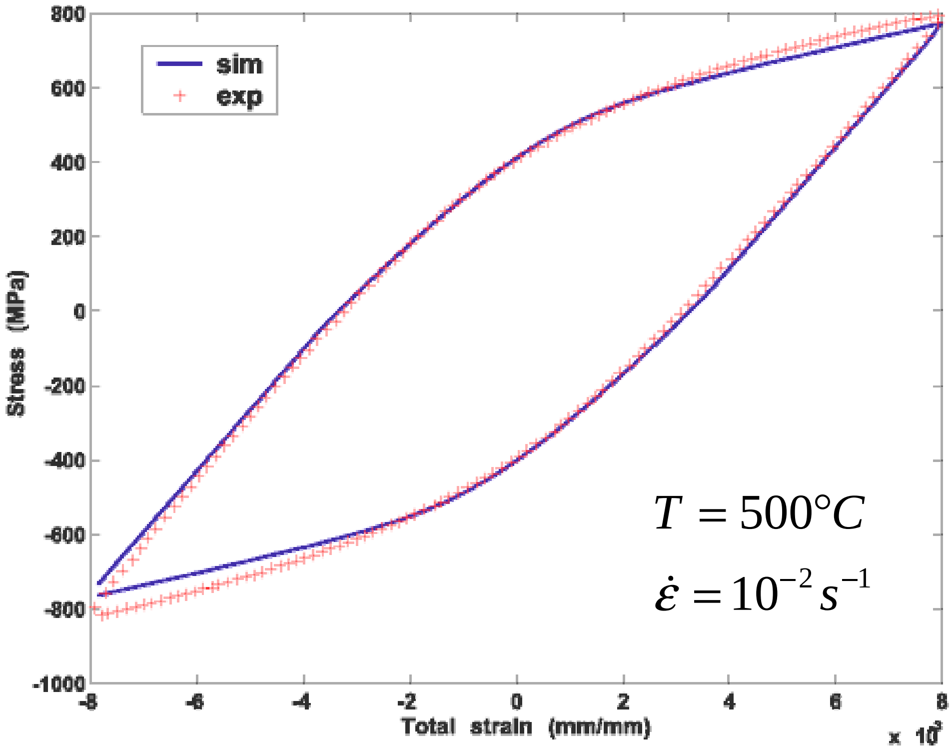

Fig.5 : Strain-controled fatigue test

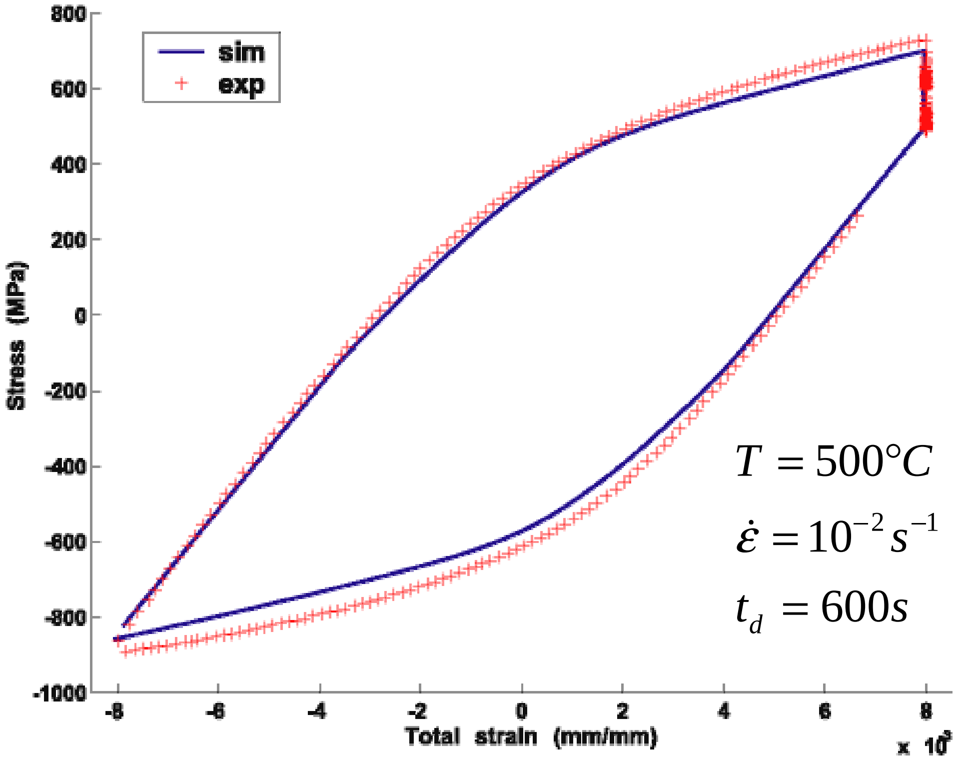

Fig.6 : Strain-controled fatigue-relaxation test

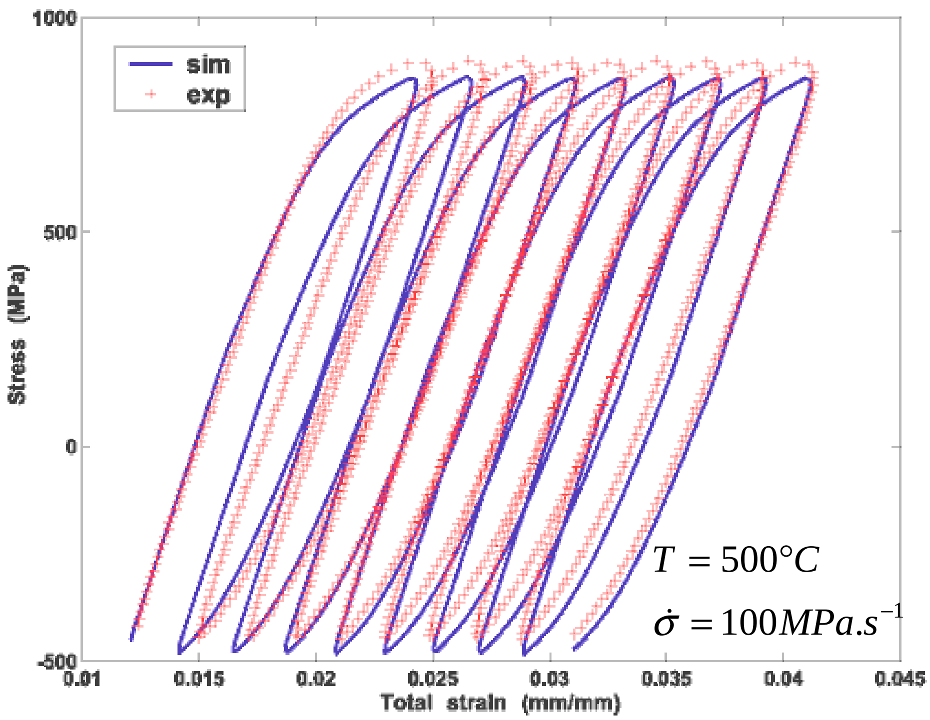

Fig.7 : Stress-controled test

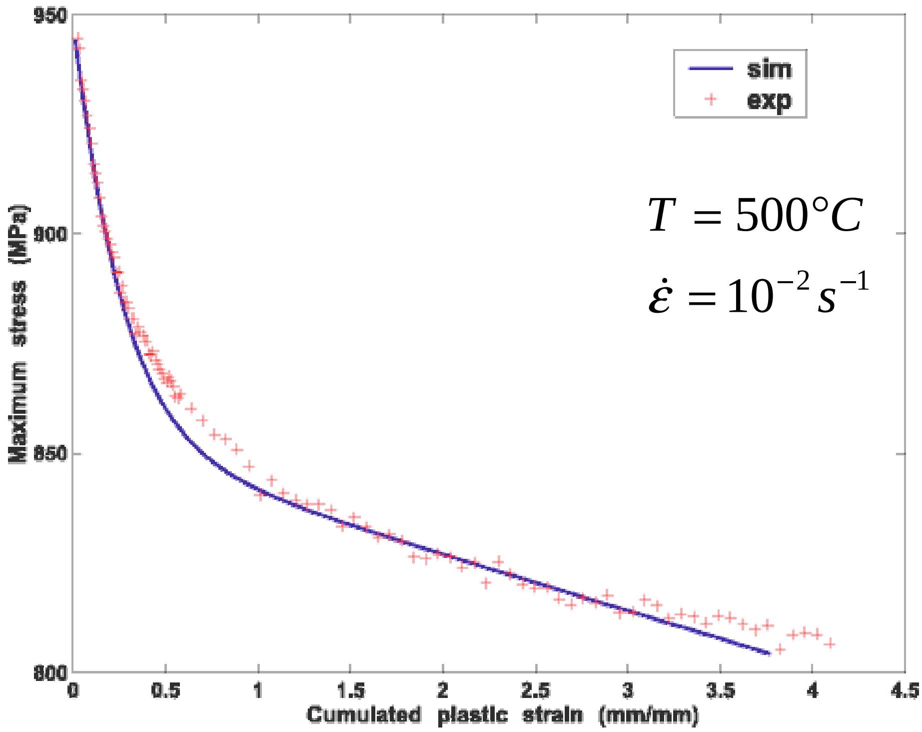

Fig.8 : Maximum stress evolution versus cumulated plastic strain

CONCLUSION

An elasto-viscoplastic cyclic model was formulated to describe the behaviour of tempered martensitic tool steels subjected to typical loads induced by industrial processes. For the temperature range between 20 and 500° C, this model is able to describe both the cyclic softening of the 55NiCrMoV7 steel and ratcheting phenomenon induced by structure effects inside the tool. Moreover, some aspects linked with the forming process like strain rate variation or the description of the dwell times, are equally considered. Besides, note that important microstructure evolutions occur when the temperature level exceed 560° C (tempering temperature), and of course, in that case, the limits of the model are reached, indeed, the previous formulation is unable to describe such evolutions.
The following work will be focused on model validation. The different parameters, even if only are identified from one-axial tests, are adequate to get a good description of the three dimensional behaviour of the material [11]. After implementation of the three dimensional model in ABAQUS™ software, axisymmetric samples with various stress concentrations will be simulated and results compared to experimental ones.

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