EXPERIMENTS AND SIMULATION OF TRANSFORMATION INDUCED PLASTICITY UNDER MULTIAXIAL LOADING FOR A 16MND5 FERRITIC STEELS

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ABSTRACT

This paper is concerned with the behaviour of a 16MND5 Steel (french PWR vessel material) under complex loading during phase transformation. A simple meso-model for multiphase materials is explained where each metallurgical phase is represented. Then, we describe a new thermo-mechanical experimental device for the analyse of transformation plasticity under coupled tension-torsion loading and give experimental results. Finally, we give the example of numerical simulation of a disk heated by a laser spot and compare the results with experimental results.

INTRODUCTION

During welding or heat-treatment operations or even during severe accidents in nuclear reactors, for example, on civilian nuclear facilities, steel parts are subject to large thermal and mechanical actions leading to complex, multiaxial local loads [7]. In these situations, the steel materials employed undergo phase transformations under stress. Reliable numerical simulation of such processes and severe situations require the use of sophisticated models which take into consideration, on the one hand, the thermal, mechanical and metallurgical (phase transformation) behavior of these steels and, on the other hand, the coupling effects between these various physical phenomena. Indeed, interactions do exist among thermics, mechanics and metallurgy. The work we are presenting is part of a continuous study [10] of the thermal, metallurgical and mechanical characterization of 16MND5 ferritic steel. In the previous works, coupling between thermics and mechanics, on the one hand, and thermics and metallurgy, on the other, was studied and modelled precisely [10]. In this study, we will focus more particularly on the influence of metallurgy on mechanics. Let us recall that if a mechanical loading is applied during the phase change there is a resulting residual strain called transformation induced plasticity (TrIP)[5, 9]. All the models proposed are based on experimental observations under uniaxial loading. However, a recent study [12] shows that transformation plasticity is influenced by the multiaxial character of the mechanical loading. Therefore, the main objective of our study is to expand the experimental data base of multiaxial load cases.

The paper has three parts. The first part deals with the meso-model developped, where the behaviours of each of the present phases in the materials are represented. In the second part, we describe a new thermo-mechanical experimental device. We show how the specimens react during phase transformation under different tension-torsion loadings. Finally, the third part is devoted to the use of the proposed model in order to simulate a test on disk heated by a laser spot, which is representative of a welding operation. Simulations and tests are compared.

MODELS

Two classes of models including phase transformation for steels are used (or studied). The most simple is an homogenous model where the phases is represented by an unique “equivalent” homogenised model. The same type of behaviour (elasto-plastic for example) whose caracteristics are calculated by a basic mixure rule [8, 6, 7]. Such models raises two main drawbacks : First, you can’t mix different type of behaviour (eg. elastoplastic for a phase and viscoplastic for the other phases) second the mixure of two viscous materials with different viscous exponents is not a viscous model with the mixure of the exponents. Others researchers adopt most fine models based on micromecanics considerations [2, 3]. However, these sophisticated models needs a lot of internal variables, thus they are not used to calculate real structures. Hence, we have looked for a new model most flexible than mixure rule model and less expensive in calculation than the second one. The model is denoted meso-model. The following rate equation describe the meso-model :

$$\dot{E}^{thm} = \dot{E}^{t} - \dot{E}^{pt}$$

Where $\dot{E}^{t}$ is the mean total strain rate, $\dot{E}^{pt}$ is the phase transformation strain rate and $\dot{E}^{thm}$ is the mean thermo-elasto-visco-plastic strain rate. For each phase i we have make the voigt hypothesis wich writes :

$$\dot{\varepsilon}_i^{thm} = \dot{E}^{thm}$$

and we decompose this strain rate as usual :

$$\dot{\varepsilon}_i^{thm} = \dot{\varepsilon}_i^{e} + \dot{\varepsilon}_i^{vp} + \dot{\varepsilon}_i^{th} + \dot{\varepsilon}_i^{tm}$$

Where $\dot{\varepsilon}_i^{e}$, $\dot{\varepsilon}_i^{vp}$, $\dot{\varepsilon}_i^{th}$, $\dot{\varepsilon}_i^{tm}$ are respectively the elastic, viscoplastic, thermal and volume phase change strain rate of phase i. We then use for each phase the choosen material model and we obtain for each phase :

$$\dot{\sigma}_i = f_i(\sigma_i^{(1)}, A_i, T, \dot{\varepsilon}_i^{thm})$$

In this equality, f_i is the model equation, A_i the internal variables and $\sigma_i^{(1)}$ the stress of the phase. Theses equations allow to calculate for a small time increment Δt the final stress state $\sigma_i^{(2)}$ for each phase. The homogeneised stress is given by $\Sigma^{(2)} = \sum_{i=1}^{n} z_i \sigma_i^{(2)}$. In these equations, the strain rate for each phase are the usual values. $\dot{\varepsilon}_i^{tm}$ and $\dot{E}^{pt}$ are given by :

$$\dot{\varepsilon}_i^{tm} = \dot{z}_a \Delta\varepsilon_{\alpha,\gamma}^{20^o} \quad \text{et} \quad \dot{E}^{pt} = K(\Delta\varepsilon_{\alpha,\gamma}^{20^o}, \sigma_a^{y}) \cdot f'(z_a)\dot{z}_a \cdot \Sigma^D \quad [8]$$

Let us observe that by this method we can choose **any** model for each phase i. This model have been implemented in CASTEM 2000 Code [11]. The mechanical phase model are the usual one hence we concentrate now in the transformation plasticity models.

EXPERIMENTS

The material studied is the French 16MND5 vessel steel whose composition is given in Table 1. This is a low-alloy, low-carbon steel. Like all ferritic steels, it can undergo a variety of transformations depending on the cooling rate.

Table 1: **Chemical composition of 16MND5 in % mass**

C	S	P	Si	Mn	Ni	Cr	Mo	Cu	Co	Fe
0,16	0,007	0,010	0,015	1,30	0,74	0,18	0,48	0,06	0,01	balance

The tension-torsion test specimen is a thin tube connected to two massive heads by a wide fillet. The central part, a tubular cylinder of internal diameter $\phi_{int} = 23.4\,mm$ and external diameter $\phi_{ext} = 25.4\,mm$, enables us to obtain a quasi-homogeneous stress field of the following form :

$$\Sigma = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & \tau \\ 0 & \tau & \sigma \end{bmatrix}_{(\vec{e_r},\vec{e_\theta},\vec{e_z})} \qquad E = \begin{bmatrix} \varepsilon_{rr} & 0 & 0 \\ 0 & \varepsilon_{\theta\theta} & \frac{\gamma}{2} \\ 0 & \frac{\gamma}{2} & \varepsilon \end{bmatrix}_{(\vec{e_r},\vec{e_\theta},\vec{e_z})}$$

The axial and shear stresses are calculated respectively from the tension force F and the torsion torque C:

$$\sigma = \frac{F}{S} \qquad \text{where} \qquad S = \frac{\pi}{4}(\phi_{ext}^2 - \phi_{int}^2) \tag{1}$$

$$\tau = \frac{C}{\frac{I_0}{r_{moy}}} \qquad \text{where} \qquad I_0 = \frac{\pi}{32}(\phi_{ext}^4 - \phi_{int}^4) \qquad \text{and} \qquad r_{moy} = \frac{(\phi_{ext} + \phi_{int})}{4} \tag{2}$$

The tests are performed on a *MTS TTC* servo-electro-hydraulic tension-torsion machine and heating is provided by electromagnetic induction. Cooling is achieved by injecting argon inside the test specimen. The gas enters through the lower wedge brace, sweeps over the wall of the test specimen to cool it and escapes through the upper wedge brace (Figure 1).Various calibration tests showed that the heating rate may come close to $60\,^oCs^{-1}$ and the cooling rate to $-40\,^oCs^{-1}$. During the tests, the temperature is measured via twelve thermocouples welded in the useful zone. The strains (ε and γ) are measured using a water-cooled MTS 632.68F biaxial high temperature extensometer. This extensometer was modified to reduce the distance between extension rods to 15 mm.

The first tests concerned bainitic transformation. The onset of bainitic transformation is 600 ^oC and, at that temperature, the yield stress σ^y of bainite is $100MPa$ [10]. All the specimens were heated at a rate of $10\,^oCs^{-1}$ and were maintained at a temperature of $900\,^oC$ for $30\,s$, then cooled at a constant rate of $-3\,^oCs^{-1}$. Three test specimens were used in this first series of tests. Each specimen was subjected to a succession of six thermomechanical load patterns as described on Table 2. Figure 2, show the axial and shear strains evolutions during the different phases of the third test. First, let us observe that the kinetics of the transformation is not affected by the mechanical loading, which can be easily deduced from the difference between the free dilatometry curve and the dilatometry curve under torque. This result is consistent with the works of Gautier [4], who observed no noticeable differences in the case of small applied loads. We also note that the shear strain remains constantly zero during heating. Qualitatively, we observe that a torque alone causes only a shear plastic strain, a force alone causes an axial strain and a torque plus a force generate axial and shear strains. We must now extract from these curves the transformation plastic strains. For this purpose, we consider that the total strain is the sum of the elastic strain, the thermal strain and the transformation plastic strain. Figure 3 represent the equivalent transformation plastic strain versus the equivalent von Mises stress. It is clear that for the bainitique transformation, transformation plasticity strain is proportionnal to the stresses deviatoric tensor.

Table 2: **Stresses (MPa) applied in the different phases of the three tests**

Tests	Phase 1	Phase 2
1	$\sigma = 0 \quad \tau\sqrt{3} = 0$	$\sigma = 0 \quad \tau\sqrt{3} = 30$
2	$\sigma = 0 \quad \tau\sqrt{3} = 0$	$\sigma = 0 \quad \tau\sqrt{3} = 45$
3	$\sigma = 0 \quad \tau\sqrt{3} = 0$	$\sigma = 0 \quad \tau\sqrt{3} = 60$
Tests	**Phase 3**	**Phase 4**
1	$\sigma = 30 \quad \tau\sqrt{3} = 0$	$\sigma = 21 \quad \tau\sqrt{3} = 21$
2	$\sigma = 45 \quad \tau\sqrt{3} = 0$	$\sigma = 32 \quad \tau\sqrt{3} = 32$
3	$\sigma = 60 \quad \tau\sqrt{3} = 0$	$\sigma = 42 \quad \tau\sqrt{3} = 42$
Tests	**Phase 5**	**Phase 6**
1	$\sigma = -30 \quad \tau\sqrt{3} = 0$	$\sigma = 21 \quad \tau\sqrt{3} = 21$
2	$\sigma = -45 \quad \tau\sqrt{3} = 0$	$\sigma = 32 \quad \tau\sqrt{3} = 32$
3	$\sigma = -60 \quad \tau\sqrt{3} = 0$	$\sigma = 42 \quad \tau\sqrt{3} = 42$

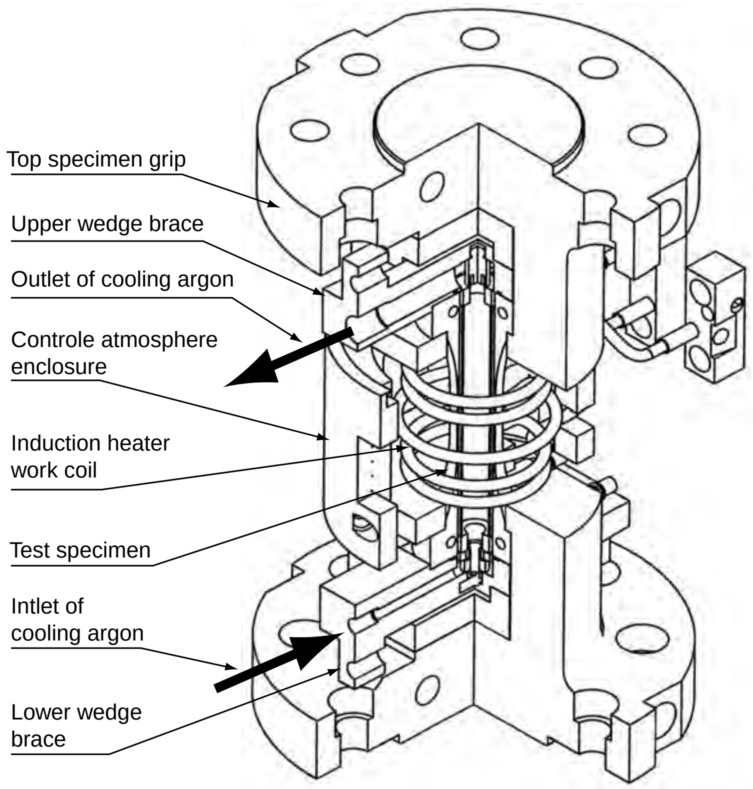


Fig. 1: **Section view of the experimental device**

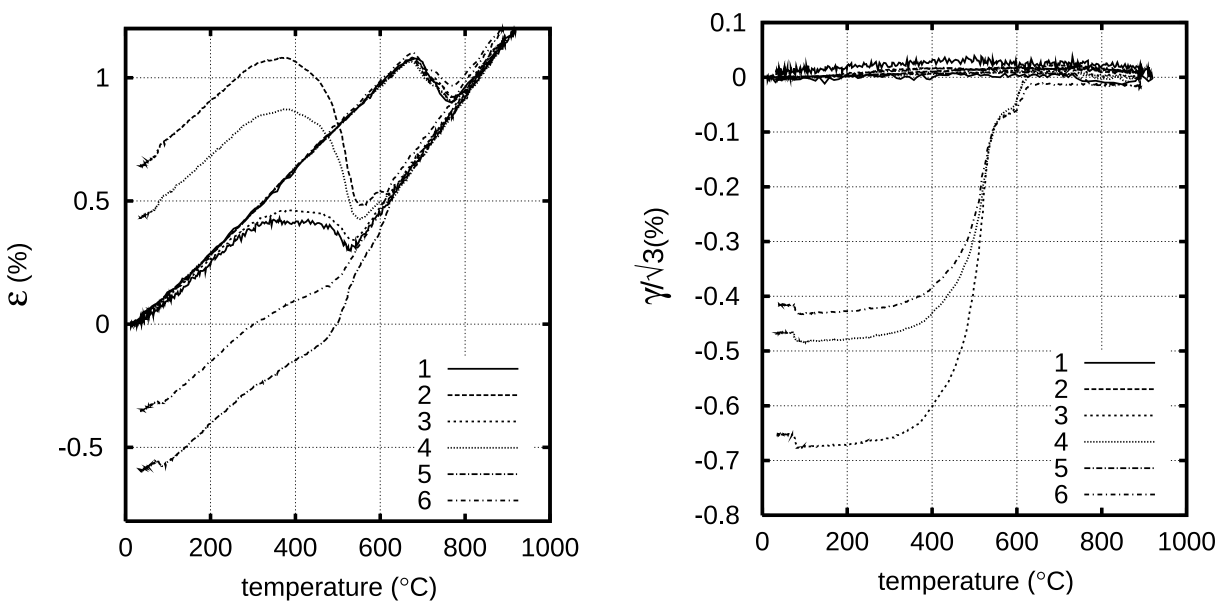


Fig. 2: **Evolutions of total axial strain and shear strain during the test 3**

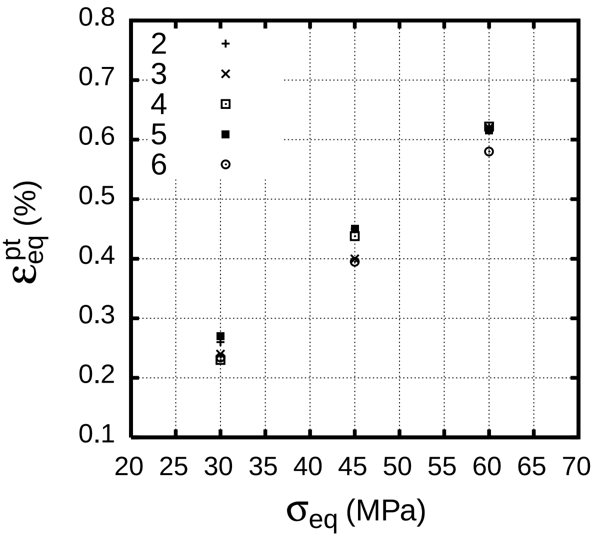
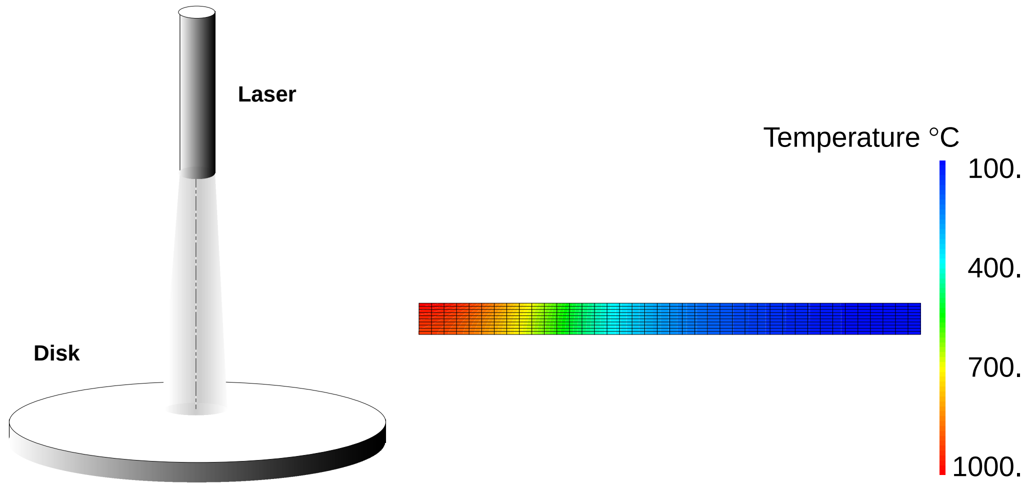


Fig. 3: **Equivalent transformation plastic strain versus the equivalent von Mises stress**

NUMERICAL SIMULATION

The simulation we present, deals with a test realised at the 'INSA de Lyon' [1]. The aim of the test is to analyse residual strains and stresses induced by welding. The test consisted of a 160 mm diameter and 5 mm thick 16MND5 steel disk heated in its center by a laser during 70 seconds then cooled by natural convection (figure 4(a)). The measured quantities are temperatures on higher and lower face, vertical displacement on the center of the disc and residual stresses obtain by X diffraction at the end of the test. For the numerical simulation, we suppose the problem is axisymetric, the mesh uses 320 QUA4 elements. The calculation needs two steps. First, we calculate temperatures and phase proportions on the structure at each time (see figures4(b) and 5) [10]. Second, we compute the mechanical state, using, the proposed model and large displacement analysis with castem 2000 code. The imposed loadings are temperatures and phase proportions. Two models are tested, first, we use a classical mixure rule model with elasto-plastic behaviour and in the second case, we use our meso-model with differents elasto-visco-plastic behaviour for each phase (see results on figures 6,7,8). The figures 7 and 8 show that the levels of displacement and hoop stresses obtained with the meso model are in good agreement with the experimental results that the mixure rule model is much less accurate. A carefull analisys shows that the viscous behaviour of some of the phases is the most sensitive parameters.



(a) Laser heated disc (b) Temperatures at the end of heating

Fig. 4: Laser heating

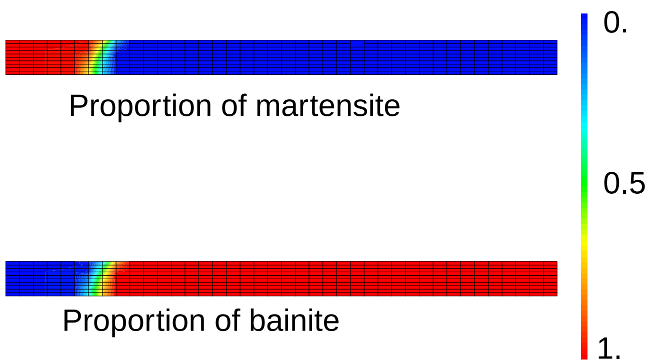


Fig. 5: Proportion of phases at the end of experiment

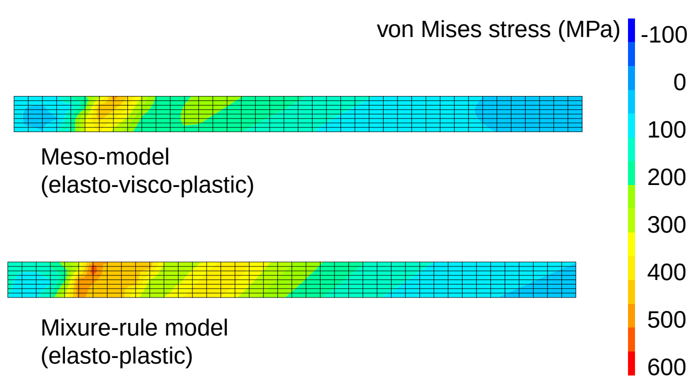


Fig. 6: Von Mises stresses

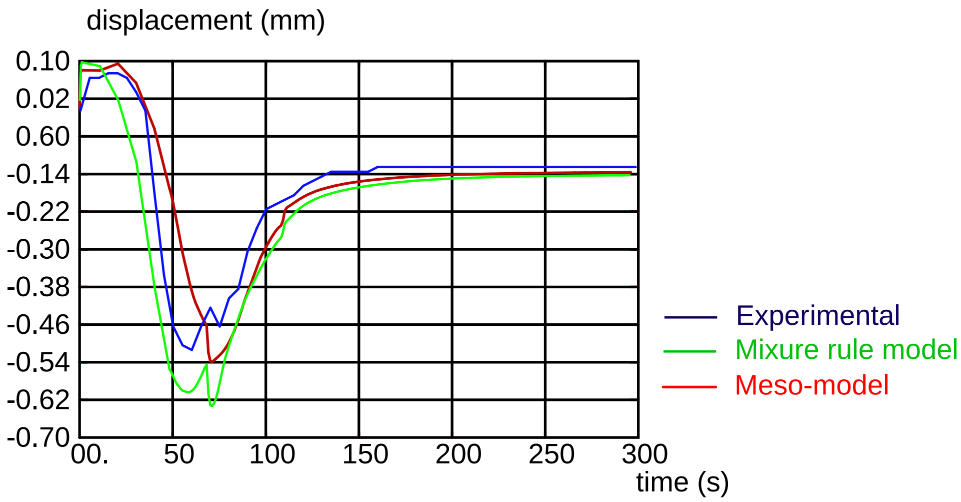


Fig. 7: **Vertical displacement during test**

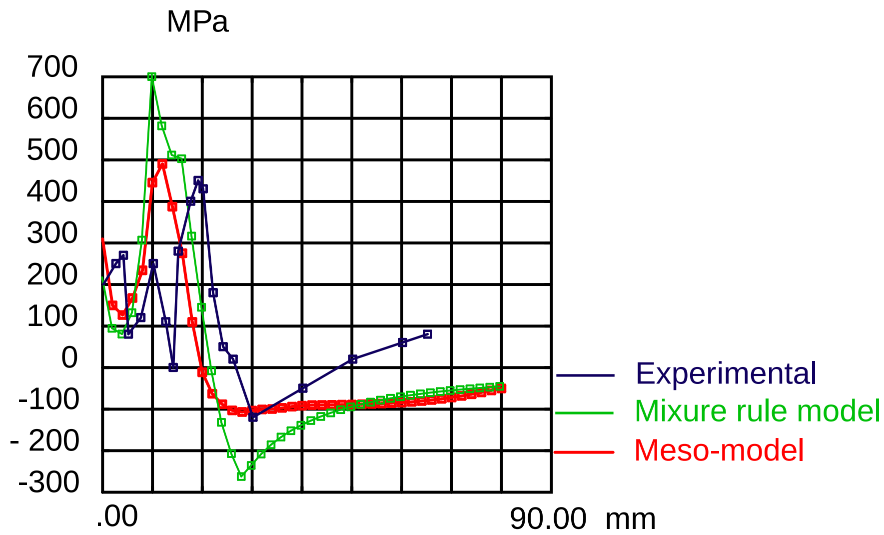


Fig. 8: **Residual hoop stresses on higher face**

CONCLUSION

This paper is devoted to the study of mechanical phase transformation modelisation for 16MND5 PWR reactor steel. A new experimental device allow us to show that for bainite transformation the transformation plasticity is governed by the deviatoric stress. A meso model is presented which enable to mix phases, each of them having its own type of constitutive model. The model is used successfully to simulate an experimental test and allows good prediction of residual stresses.

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