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Michel Coret, Alain Combescure. Comparison of two transformation plasticity models, with and without kinematic hardening for bainitic transformation under non-proportional loading path. *Journal de Physique IV Proceedings*, 2004, 120, pp.177-183. 10.1051/jp4:2004120020 . hal-04598310

HAL Id: hal-04598310

<https://hal.science/hal-04598310>

Submitted on 15 Jun 2024

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Comparison of two transformation plasticity models, with and without kinematic hardening for bainitic transformation under non-proportional loading path

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Abstract. This article deals with the multiphasic, anisothermal behaviour of 16MND5 steel under complex loading. We are focusing more specifically on the modelization of transformation plasticity induced by proportional or nonproportional biaxial loading during the bainitic transformation. A first part recalls Leblond's transformation plasticity model with or without hardening. We also describe the experimental setup used to get transformation plasticity tests under tension-torsion loadings. The last part deals with the TrIP models (with or without hardening) identification and their use for the nonproportional tests simulation.

1. INTRODUCTION

The prediction of the distortions and the residual stresses induced by welding operation or heat treatment needs the perfect knowledge of thermomechanical behaviour of materials. Currently, the studies try to predict this behaviour, and especially during the solid-solid phase changes. In this particular case, behaviours must take into account transformation induced plasticity (TrIP) phenomenon. Let us recall that two effects are usually quoted to explain this phenomenon. First, the Greenwood and Johnson effect [6] comes from the elastic and plastic accommodation between the different phases. Second, the Magee effect [9] represents the orientation process due to formation of the preferred martensite variants. One of today's challenge is to obtain a theory able to describe both effects. An other ambitious objective is the qualification of the different TrIP models under complex loadings, closer to the real situations. Our work concern a low alloy, low carbon steel for which phase transformations can be martensitic or bainitic during cooling and austenitic during heating process. Many tests have been performed [2] for various transformations under biaxial loadings. It emerges of the abovementioned study that the simulation of TrIP tests under constant stresses is good with the Leblond's model based on ideal-plastic phases [7], for austenitic and bainitic transformations. This type of model cannot predict the stress reversal effect observed on unloading test as we can see on figure 1. In that case, the introduction of hardening phenomena in the phase behaviour should be able to improve the prediction. The question also arises for more complex loading paths as butterfly test 3(e). Figure 2 shows the simulation of a butterfly test using Leblond's model and the experimental result. One can remark that this model does not allow to follow the evolution of TrIP strains during the test due to an artificial "dumping" effect. TrIP models, including hardening effect, should describe better the tests under complex loadings.

This paper consists of three parts. The first part deals with Leblond's model. We recall the expression of the TrIP strain rate obtained for a material containing two ideal-plastic phases or kinematic hardening plastic phases. The second part shows the different tension-torsion tests performed. Finally, the last part proposes to identify the two TrIP expressions on the stress holding tests and the unloading tests. The last simulation shows how the kinematic hardening TrIP model performs on a butterfly test.

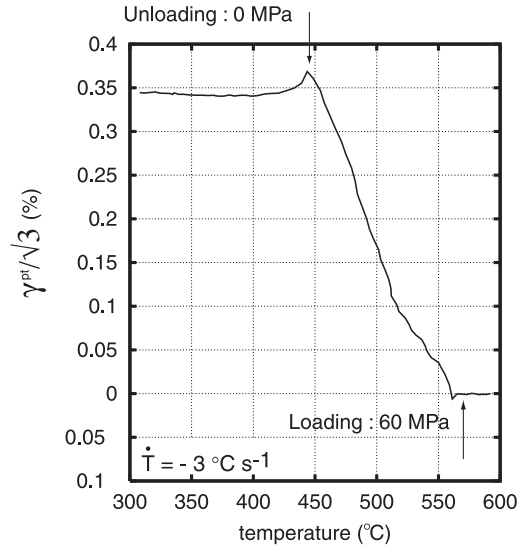


Figure 1. Evolution of shear TrIP strain during unloading.

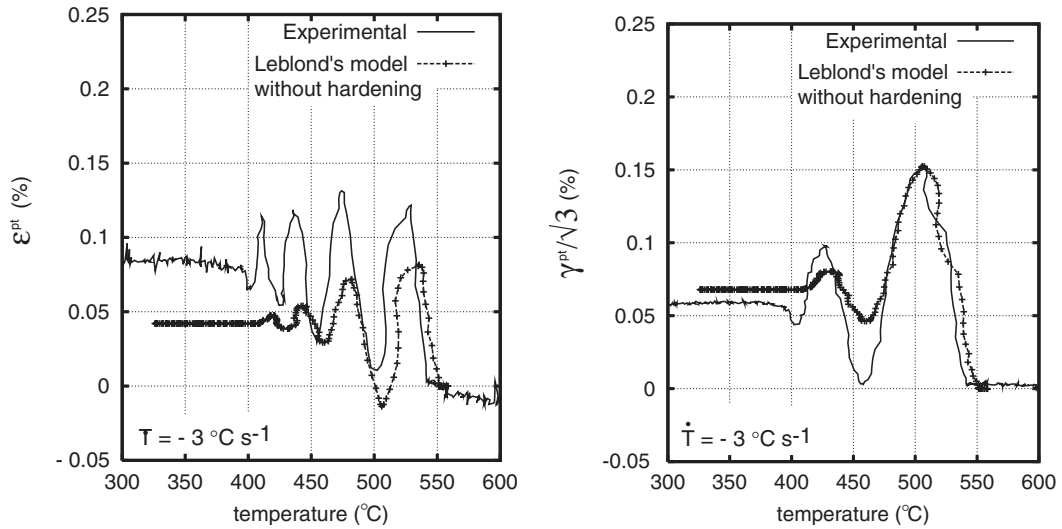


Figure 2. Evolution of axial and shear TrIP strains during butterfly test.

2. LEBLOND'S TRANSFORMATION PLASTICITY MODEL WITH AND WITHOUT HARDENING

During the Eighties, Leblond *et Al.* published some articles dealing with modeling of the A535 steel behaviour during phase transformation. The authors determined the homogenised behaviour of a material containing two ideal-plastic phases. Then, in an other article, the model was extended to take into account the coupling between TrIP and strain hardening phenomena. In these models, the Magee effect is neglected.

If the elastic compliance tensor is the same in each phase, the macroscopic total strain rate is equal to:

$$\dot{\mathbb{E}}^t = \dot{\mathbb{E}}^e + \dot{\mathbb{E}}^{thm} + (\dot{\mathbb{E}}^{pt} + \dot{\mathbb{E}}_T^{cp} + \dot{\mathbb{E}}_\Sigma^{cp}) \quad (1)$$

1. \mathbb{E}^t is the total strain
2. \mathbb{E}^{thm} is the thermal and metallurgical strain, deduced from the free dilatometry
3. \mathbb{E}^e is the elastic strain, calculated using the elastic properties of each phase.
We will assume that the elastic properties are the same in each phase and depend only on temperature. Young's modulus depends on temperature and is calculated using the expression [10]

$$E(T) = 2,08 \cdot 10^5 - 1,90 \cdot 10^2 T + 1,19 T^2 - 2,82 \cdot 10^{-3} T^3 + 1,66 \cdot 10^{-6} T^4$$

where E is in MPa and T in °C. We will also assume that Poisson's ratio ν is constant and equal to 0.3.

4. \mathbb{E}_Σ^{cp} and \mathbb{E}_T^{cp} are plasticity terms proportional to Σ_{eq} (the von Mises macroscopic stress tensor equivalent) and T which, in our case, can be neglected [2]

In the case of two ideal-plastic phases [7], the TrIP strains are given by

$$\dot{\mathbb{E}}^{pt} = A \cdot f(z) \cdot \dot{z} \cdot \mathbb{S} \quad \text{with} \quad A = 3 \frac{\Delta \varepsilon_{\alpha,\gamma}^{T_{ref}}}{\sigma_\gamma^y} \quad \text{and} \quad f(z) = \ln(z) \quad (2)$$

$\Delta \varepsilon_{\alpha,\gamma}^{T_{ref}}$ is the difference of compactness between α and γ phase, σ_γ^y is the yield stress of austenite
The model was then extended to the case of two-phase elastic-plastic with kinematic strain hardening [8]. We obtain quite naturally:

$$\dot{\mathbb{E}}^{pt} = A \cdot f(z) \cdot \dot{z} \cdot (\mathbb{S} - \mathbb{X}_\gamma) \quad \text{with} \quad \dot{\mathbb{X}}_\gamma = H_\gamma(T) \dot{\mathbb{E}}^{pt} \quad (3)$$

where H_γ is the hardening parameter of the austenite.

Others advanced models are also available. In this paper, Fischer *et Al.* [5, 11, 12, 14] predict the thermomechanical behaviour of the Cr-Ni-Mo-Al-Ti maraging steel. Working on the martensitic transformation, the Magee effect and the Greenwood and Johnson effect are both included in their model. The current research of this group deals with the back stress effect and the coupling between the applied stress and the transformation kinetics (in a multiaxial framework). Some other works are also about the couplings between stress and transformation kinetics [4].

However, these models are based on tests which are mainly uniaxial or biaxial tests where the stresses applied are constant or variable step wise [1, 13, 15]. Here, the stress rate is either zero or infinite. There is a lack of tests with non prportional loadings.

3. EXPERIMENTAL SETUP, LOADINGS AND DATABASE

The material studied is the low carbon 16MND5 steel used in french PWR vessels. The composition is given in table 1. It is a low alloy steel is used in a bainitic form. This material was chosen due to its excellent quenching capability and its high mechanical properties. As all the low carbon steel, it has different transformations. The heating causes austenitic transformation, where α phase changes to γ and where the carbon diffuses. During cooling, three types of transformation are possible. The slowest produces a ferritic-perlitic structure whereas the fastest transformation ($\dot{T} < -50 \text{ }^\circ\text{C s}^{-1}$) is martensitic. At lower cooling rates, the bainitic transformation mechanism appears. We focus in this paper on the bainitic transformation.

Table 1. Chemical composition of 16MND5 in % mass

C	S	P	Si	Mn	Ni	Cr	Mo	Cu	Co	Fe
0.17	0.002	0.004	0.25	1.44	0.75	0.20	0.51	0.01	0.004	balance

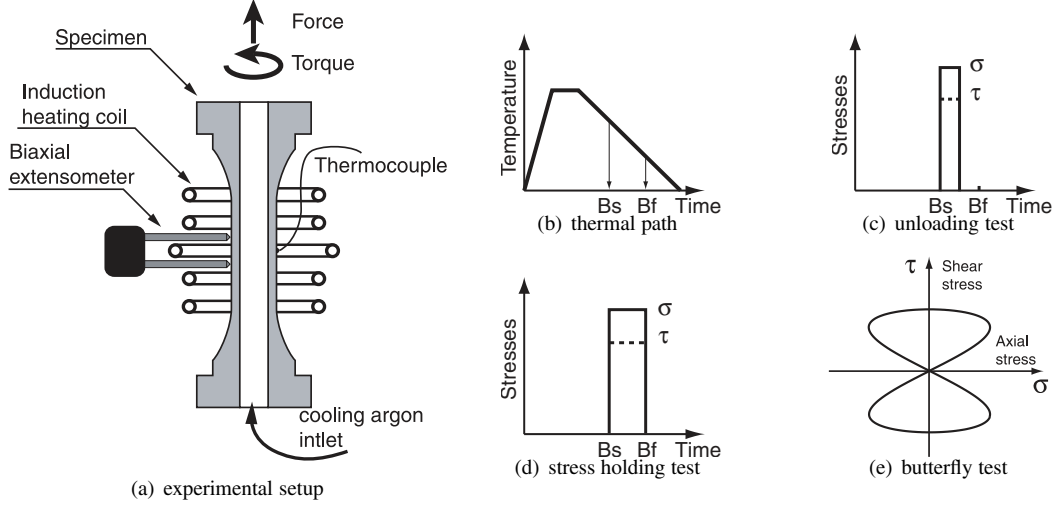


Figure 3. Experimental setup, thermal and mechanical loadings.

The tension-torsion specimen is a thin tube connected to two massive heads. The tests were done at the LMT-Cachan Laboratory [2, 3]. The mechanical loading was applied using an electro-hydraulic tension-torsion servo testing machine. During the tests, we measure the effort, torque, displacement, rotation, the axial and shear strains. Thus, twelve thermocouples welded on the measurement zone (see figure 3(a)). For all mechanical loadings, the same thermal loading is applied (figure 3(b)). The specimens are heated at a temperature greater than the austenitic transformation temperature: 900 °C, maintained at high temperature during 30 seconds then cooled to room temperature at a -3 °C s^{-1} cooling rate. The transformation plasticity tests consist in applying stress between the bainite start temperature (B_s) and the bainite finish temperature (B_f). Three kind of tests have been done. In the first test, the loading is constant during the transformation as we can see in the figure 3(d). In the second test, the mechanical loading is interrupted before the end of the transformation (fig.3(c)). During the last kind of test, the axial and shear stresses evolve during the transformation. On a butterfly test, stresses vary sinusoidally (fig.3(e)).

4. IDENTIFICATION OF THE DIFFERENT MODELS AND SIMULATION OF NONPROPORTIONAL LOADING PATH CASES

4.1. Identification

The identification of the TrIP without hardening expressions (see equation 2) only need data from constant stress tests. The evolution of the volume fraction z and the difference of compactness $\Delta\varepsilon_{\alpha,\gamma}^{T_{ref}}$ are determined with the free dilatometry. In that case, the only objective of the identification is to fit the yield stress of austenite (considered constant during the transformation). Thus we obtain for the bainitic

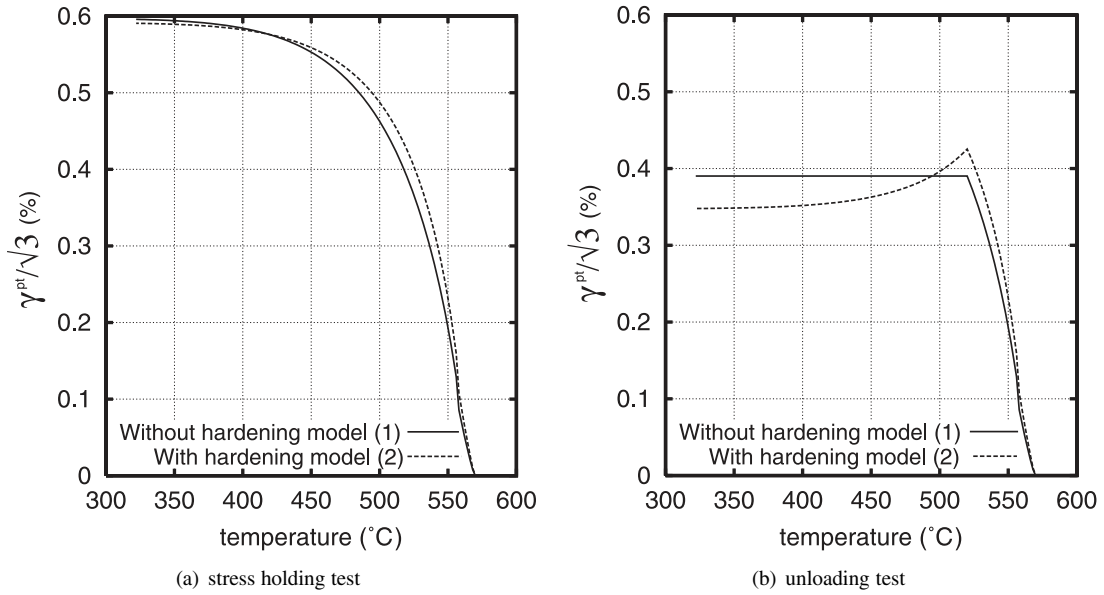


Figure 4. Computation of shear TriP strain during constant stress and unloading test with the elastoplastic model and the elastoplastic with hardening model.

transformation: $\sigma_{\gamma}^y = 140$ MPa. The first simulation is plotted on figure 4(a) curve 1.

We use the interrupted load test (figure 1) to identify kinematic hardening constants of last Leblond's Model. The test use was loaded by a stress of 60 MPa. The fitted hardening parameters are $H = 3000$ MPa and $\sigma_{\gamma}^y = 125$ MPa. The computed results obtained with these constants are displayed on figure 4(b). This figure shows that kinematic hardening is necessary to represent interrupted test and the comparison with figure 1, shows that the fitted values give a good representation of experiments.

4.2. Nonproportional loading paths

We now use Leblond's model without hardening to compare with butterfly experimental results. The comparison is displayed on figure 2. For the elongation, the final predicted strain is 0.05% whereas the experimental one is 0.1%. For shear strain and elongation the strain range damp much more faster with the model than in the experiments. We are now going to compare only on theoretical results the effect of kinematic hardening. We observe on figure 5 that the kinematic hardening model is not very beneficial: first, it only increases of about 10% the strain range. Second, the final predicted strains are decreased when they should be increased. The crude kinematic hardening model identification proposed in this paper is not very effective.

5. CONCLUSION

The optimisation of welded structures needs a perfect knowledge of the thermomechanical behaviour of materials under complex loadings. In our case, for the 16MND5 low carbon steel, austenitic, bainitic and martensitic transformation can occur under mechanical loadings. We have chosen to the Leblond's model which only predict the Greenwood and Johnson effect, the main effect in the bainitic transformation. Numerous biaxial tests have been realized to qualify this model. We can say that we can match quite surely the biaxial tests under constant stresses with Leblond's model without hardening. On

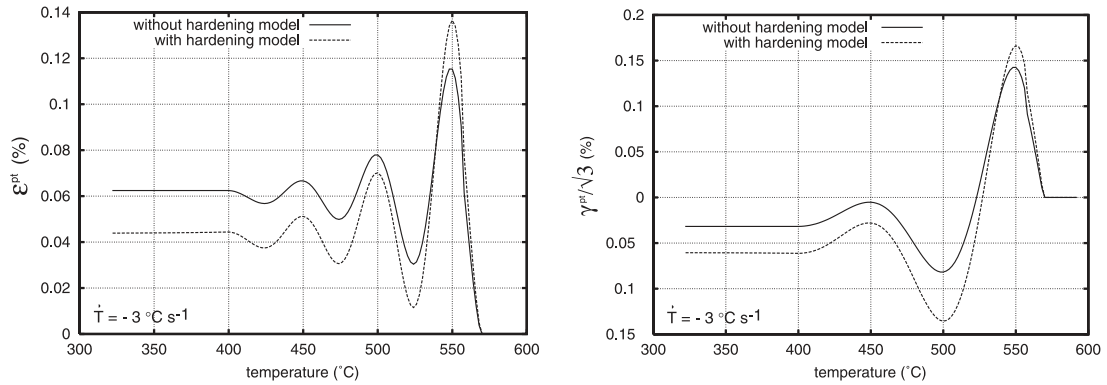


Figure 5. Computation of axial and shear TRIP strains due to butterfly loading path with the elastoplastic and the elastoplastic with hardening models.

the other hand, we could not precisely reproduce with this model the complex non proportional tests. Leblond's model with hardening improve here some things. For more complex loadings such as butterfly tests, the responses of Leblond's model with or without hardening are not drastically different. The "damping" effect produced by the model without hardening is still present in the model including the hardening effect.

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