Transactions of the **14th International Conference on Structural Mechanics in Reactor Technology** (SMiRT 14), Lyon, France, August 17-22, 1997 **BLDW/13**

Phase transformation effects on mechanical behaviour of steel vessel

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ABSTRACT

This work is a contribution concerning the study of the mechanical consequences of phase transformations on the french steel vessel (16MND5 in the AFNOR norm). In order to have a sufficient data base for the studied steel, a specific experimental device has been carried out, the program defined for this objective is given in this paper. The test results are used for the identification and the evaluation of the models related to the studied phenomena. Two test results with their numerical simulation are presented in this paper.

INTRODUCTION

In a welding process there exists a particular zone called Heat Affected Zone (HAZ) where phase transformations in a solid state occur. In order to estimate the residual stresses due to that process, a large program is defined on a carbon manganese steel (16MND5 in the AFNOR norm), generally used for the water pressure vessel,. This program includes two parts, the goal of the first one is to have an experimental data base concerning the thermomechanical behaviour of the steel including phase transformations effects. The main objective of the second part of the program is to simulate the actual thermomechanical conditions of the HAZ on two different specimens : a disc and a thick cylinder. The residual stresses created by this process will be experimentally 'measured' and then compared to the numerical simulation. On the other hand, the tests concerning the data base are simulated by certain existing models. The predictions of those simulations are then compared to the experimental results.

The present work concerns only the 'data base' program for which some details are given in the first part of this paper. The second part is devoted to a presentation of the experimental device carried out. In the third part the main constitutive equations of the considered models related to the transformation induced plasticity phenomenon are recalled. The last part is devoted to the presentation of two test results and their numerical simulations.

1. DATA BASE PROGRAM

There are four main consequences of phase transformations on the mechanical behaviour :

1. The first one is the variation of volume during phase transformation. This phenomenon is due to the difference of compacities between the 'mother' and the 'daughter' phases.
2. The second consequence is linked to the residual deformation observed when the material was subjected to an external load during the phase transformation. That deformation, which is called transformation induced plasticity, is observed even if the stress due to the applied load is largely lower than the yield stress.
3. The third consequence is related to the mechanical behaviour (stress-strain curve) of a material composed of several phases. Indeed the behaviour of the mixture depends on the one of each phase.
4. The fourth consequence of phase transformation concerns the recovery phenomena. In fact, depending on the material, the strain hardening of the mother phase could be transmitted totally, partially or not at all to the daughter phase.

The program of tests [1] was defined in order to study all consequences mentioned above. For all tests, the austenitization conditions (heating rate, maximum temperature and holding time at that temperature) are the same and similar to those concerning the HAZ in a welding process. A thermal cycle is then essentially characterised by the cooling rate, several values of the latter being defined to have a specific phase or a particular mixture. Knowing the nature and the proportion of the phases constituting the material, a monotonic tensile test gives the stress-strain curve (study of the third consequence). In order to study the second and the fourth consequences, the main parameter of the tests (in addition to the cooling rate of the thermal cycle) is the direction (tension or compression) and the intensity of the external load. This load is applied just before the starting of the phase transformation and maintained until the end of the thermal cycle. The subtraction of the strain (without the elastic part) of that cycle minus the one of the same thermal cycle, but without applied external load, gives the transformation induced plasticity (study of the second consequence). Concerning the fourth consequence, the external load is applied momentarily on the mother phase in order to have a significant strain hardening of the latter. At the end of the test, the strain hardening of the daughter phase is then compared to the one of the same phase obtained by the same thermal history but without any external load.

2. EXPERIMENTAL DEVICE

A specific experimental device was performed [1] in order to carry out the data base program presented in the above section. The specimen is a thin-walled tube (Figure 1), the chosen geometry enables to blow into the specimen a current gas for its cooling and minimises the radial thermal gradient. The length of the studied zone is 15 mm, in that part of the tube the temperature can be considered as uniform. The specimen can be subjected to either compression or tension by a hydraulic actuator which is able to apply up to 100 kN. The test can be force-driven or displacement-driven while the heating rate, the holding time at the maximum temperature and the cooling rate can be regulated to desired values. The tube is heated by means of Joule effect, the thermal device allows to have a heating rate up to 125°C/s and a maximum temperature more than 1200°C. The cooling is made essentially by an internal nitrogen current, the maximum and the minimum possible cooling rates are equal respectively to -140°C/s and -0.1°C/s. Argon little flow circulates on the external surface of the tube in order to avoid the oxidation of the latter at high temperature. For the defined tests, the heating rate (80°C/s) and the maximum temperature (1100°C) are the same. The cooling rate, which remains constant for the same test, is chosen according to the desired phase or mixture at the end of the thermal cycle.

Temperature measurements are performed by some thermocouples (K type, 78 µm of diameter), welded along the studied zone. The maximum uncertainty on the measured temperature is estimated at about ± 1% for 1000°C. Electrical tension is measured to follow the metallurgical evolution. The displacement of the studied zone is measured by an extensometer with an uncertainty equal to about ± 2%. The applied force is measured by means of strength transducer. Figure 2 shows a view of the experimental device.

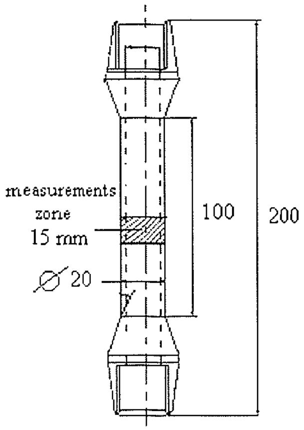

Figure 1 : geometry of the specimen

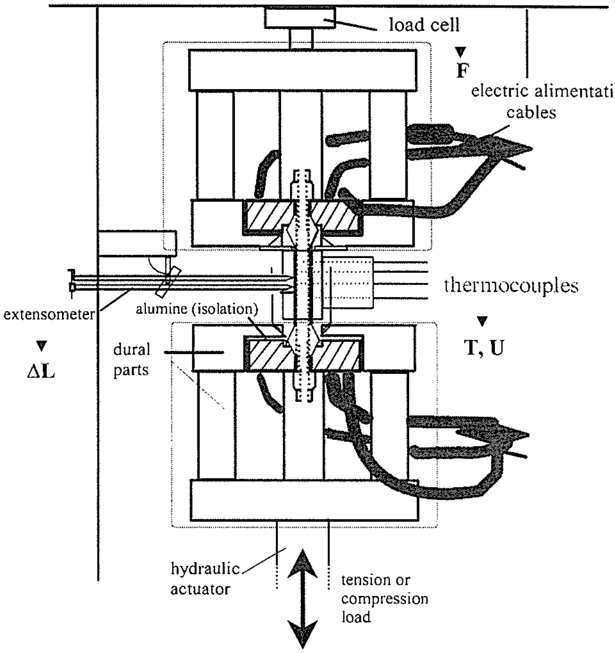

Figure 2 : experimental device

3. RESULTS DEDUCTED FROM THE TESTS

Four categories of tests are carried out, the results deducted from each category [1] are :

- Dilatometry tests : $\Delta L = f(t)$ and $T = f(t)$ give $\varepsilon^t = f(T)$ and then $z = f(T)$. ΔL, T, ε^t, t, and z are respectively the relative displacement, the temperature and the total deformation of the studied zone, the time and finally the new phase proportion. Note that in this category no external force is applied.
- Transformation induced plasticity tests : in addition to the parameters recorded in the dilatometry tests, the evolution of the transformation induced plasticity is deducted.

- Monotonic tensile tests : for the tests carried out at room temperature (mixtures without austenite), the stress versus strain curve is deducted from F = f(ΔL). For the mixtures including austenite (tests at high 'constant' temperature), the evolution of the other parameters (T = f(t) and z = f(T)) which must remain not significant is also recorded.
- Time recovery tests : those tests are carried out in two steps, the first one consists in a dilatometry test in which a force is applied momentarily before the transformation, the second step is a monotonic tensile test at room temperature. The same parameters as dilatometry and transformation induced plasticity tests are then deducted.

3. CONSIDERED MODELS

3.1 Metallurgical Model

The model proposed by Waeckel [2] is considered in order to simulate the metallurgical behaviour of the specimen subjected to a thermal cycle which leads to some phase transformations. The main features of that model are as follows : the transformation, ferritic phase → austenite, is simulated by a simplified version of the model proposed by Leblond et al. [3]. The ferritic, pearlitic and bainitic transformations are deducted from the CCT (Continuous Cooling Transformations) diagram related to the considered material. The martensitic transformation is simulated by the model proposed by Koistinen & Marbürger [4]. The necessary parameters related to the studied material are generally deducted from the considered dilatometry test.

3.2 Mechanical Models

In this paper only the simulation of the transformation induced plasticity (TIP) is considered. In that domain, the existing models can be classified into two categories : phenomenological and theoretical. In the first category, the model proposed by Desalos-Leblond-Giusti [5-6-7] is chosen and in the second category, the one proposed by Leblond et al. [8] is considered. Note that those models are based on the Greenwood & Johnson [9] mechanism which attributes the transformation induced plasticity to the microscopic plasticity generated in the weaker phase (oriented by the applied stress) by the difference of specific volumes between the coexisting phases. Generally this category of models have the same global form, indeed it is well known that the evolution of the TIP can be described by an equation which has the following form :

$$\dot{\underline{\varepsilon}}^{pt} = \frac{3}{2} k.f(z).g(\underline{S}) \qquad (1), \qquad \text{where,}$$

$\dot{\underline{\varepsilon}}^{pt}$ is the transformation induced plasticity rate tensor,

k is a parameter which depends on the material,

z is the proportion of the newly formed phase and *f(z)* is a function of z and its rate $\dot{z}$,

$\underline{S}$ is the deviator of the applied stress tensor and $g(\underline{S})$ is a function of $\underline{S}$.

In this paper, the considered models differ by the way to express *k*, *f(z)* and $g(\underline{S})$. Those differences are briefly presented in the following sections.

3.2.1 The Model Proposed by Leblond [8]

The parameter *k* and the functions *f(z)* and $g(\underline{S})$ have been deducted from a theoretical study, the proposed expressions in [8] are as follows :

$$k = \frac{-2\Delta\varepsilon_{1\to 2}^{th}}{\sigma_1^y} \qquad (2) \qquad\qquad f(z) = \begin{cases} 0 & if\ z \le 0.03 \\ Lnz.\dot{z} & if\ z > 0.03 \end{cases} \quad (3)$$

$$g(\underline{S}) = \begin{cases} \underline{S} & if\ \frac{\sigma^{eq}}{\sigma^y} \le 0.5 \\ (1+3.5(\frac{\sigma^{eq}}{\sigma^y} - \frac{1}{2})).\underline{S} & if\ \frac{\sigma^{eq}}{\sigma^y} \ge 0.5 \end{cases} \qquad (4)$$

$\Delta\varepsilon_{1\to 2}^{th}$ is the difference of thermal deformation between the mother and the daughter phases,
σ_l^y is the yield stress of the weaker phase,
σ^{eq} is the equivalent applied stress (Von Mises),
σ^y is the yield stress of the mixture,

Note that this first version of the model proposed by Leblond et al. does not include the effect of the strain hardening phenomenon of the phases. There exists a more recent version where that phenomenon is taken into account [10].

3.2.2 The model proposed by Desalos-Leblond-Giusti [5-6-7]
Considering the results of some experiments, an equation which describes the evolution of the TIP in uniaxial cases has been proposed by Desalos [5]. A generalisation of that equation for the multiaxial cases in addition to the ones where the stress is not constant was later proposed by Leblond and Giusti [6-7]. In that equation the parameter *k* is a constant which could be deducted from an uniaxial test, it is the ratio between the final value of the transformation induced plasticity and the applied stress. The functions $g(\underline{S})$ and $f(z)$ are respectively equal to $\underline{S}$ and $2(1-z).\dot{z}$, $f(z)$ has been deducted from the tests presented in [5].

4. TEST RESULTS. COMPARISON WITH NUMERICAL SIMULATIONS

4.1 Dilatometry test

The dilatometry test considered in this paper consists in a heating of the specimen (80°C/s) up to 1100°C (without holding time), followed by a cooling (-10°C/s) up to the room temperature. For the 16MND5 steel, that thermal cycle leads to a phase transformation fully martensitic.

Figure 3 gives the result of the dilatometry test and its numerical simulation. Generally, the simulation of the dilatometry test is correctly performed by the used metallurgical models. Therefore, it can be noticed on the dilatometric curve that from about 470°C up to the beginning of the martensitic transformation, the slope of the curve predicted by the simulation deviates from the experimental one. That difference could be explained either by the starting of a bainitic transformation (at about 470°C) or by the variation of the coefficient of dilation of the austenite (α_γ) versus the temperature. Indeed, in the simulation, α_γ was supposed equal to 23.5 10^{-6} °C^{-1} whatever the temperature [11]. Concerning the simulation of the martensitic transformation kinetic, it seems that the prediction given by the model proposed by Koistinen and Marbürger overestimates that kinetic at the beginning of the transformation.

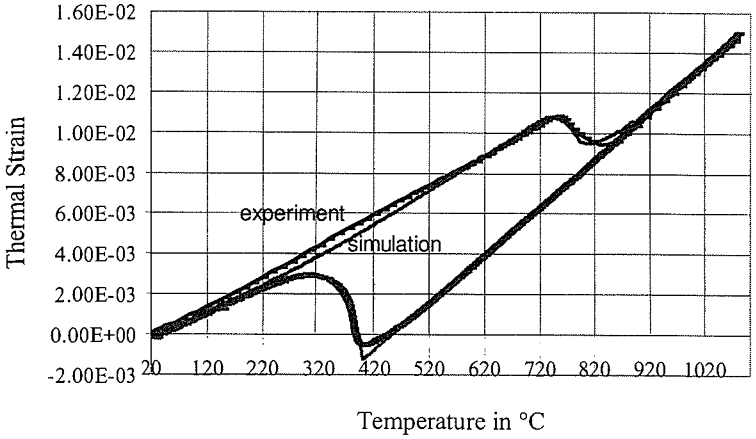

Figure 3 : Dilatometry test (heating 80°C/s to 1100°C and cooling -10°C/s) : test result and numerical simulation

4.2 Transformation induced plasticity tests

After the dilatometry test, the same thermal cycle was applied on the same tube, but during the cooling, at 435°C, an axial force was applied on the specimen and maintained up to the end of the cycle. That force induces a tension equal to 72 MPa which is equal to about a half of the yield stress of the austenite at 435°C [11].

Table 1 gives the parameters and the functions used in each simulation.

Simulation	*k*	*f(z)*	*g(S)*
S1	$0.64\ 10^{-4}\ \mathrm{MPa}^{-1}$	$2(1-z).\dot{z}$	$\underline{S}$
S2	equation (2)→$0.89\ 10^{-4}\ \mathrm{MPa}^{-1}$	equation (3)	equation (4)

Table 1 : parameters and functions used in the simulations S1 and S2.

In the numerical simulation S1, *k* was deducted directly from the considered test. *k* represents the ratio between the final value of the transformation induced plasticity (ε^{pt}) and the applied stress. In the simulation S2, *k* is given by the theoretical expression proposed by Leblond & al. (see equation (2)), the parameter $\Delta\varepsilon^{th}_{1\to2}$, which is the difference of thermal deformation between the austenite and the martensite, was supposed constant during the transformation. It was deducted from the dilatometry test at the temperature where the stress was applied (435°C), the considered value is about 0.62%. The yield stress of the austenite at 435 MPa was taken from [11], the considered value is about 140 MPa.

Figure 4 gives the TIP evolution versus the temperature deducted from the experiment and two numerical simulations of the considered test (S1 and S2).

Concerning the final values of the TIP, it is normal to have, by S1, exactly the value obtained experimentally (choice of *k*). A significant part of the difference observed between the experiment and the prediction of S2 is due to the considered value of *k*. The difference between the experimental value ($0.64\ 10^{-4}\ \mathrm{MPa}^{-1}$) and the theoretical one ($0.89\ 10^{-4}\ \mathrm{MPa}^{-1}$) could be linked to the combination of two effects : the first one concerns the assumption of ideal-plastic phases considered by Leblond & al. to establish equation (2). The results will be certainly closer to the experiment if the version (of the model) which takes into account the strain hardening of the coexisting phases (the austenite particularly) was considered. The second effect is related to the value of the yield stress of the austenite at 435°C taken into account. Indeed, it is not easy to know accurately the mechanical behaviour (stress-strain curve) of the austenite at that temperature.

Note that for a similar steel (A533), a different value of k ($\approx 1.0\ 10^{-4}$) has been experimentally obtained by Desalos [5].

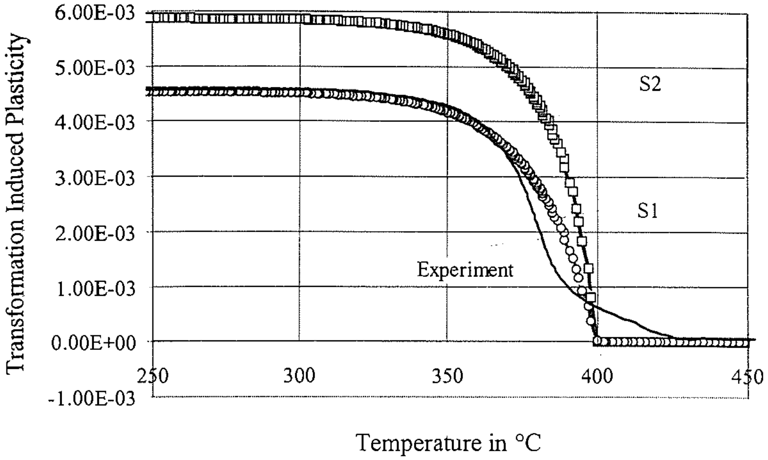

Figure 4 : Transformation induced plasticity test (heating 80°C/s to 1100°C followed by a cooling (-10°C/s) during which, at 435°C, 72 MPa was applied and maintained) : test result and numerical simulations.

Concerning the rate of the transformation, the functions considered in S1 and S2 lead approximately to the same shape. That shape is not consistent with the experimental result at the beginning of the transformation. The simulations seem overestimate the TIP rate. Indeed, at about 390°C for instance, the TIP value reaches a half of the final value but at the same temperature the experimental value does not exceed a quarter of the final value although the transformation starts later by the simulations!

The temperature at which the martensitic transformation starts (Ms) used in the simulations was deducted from the dilatometry test (without external force), but it seems that Ms is changed by the application of the external force, that effect is not taken into account by the considered metallurgical model.

CONCLUSION

This paper deals with the study of the consequences of phase transformations on the mechanical behaviour of the french steel called 16MND5 in the AFNOR norm. For this objective a specific experimental device has been carried out and a large program including the study of the most mechanical consequences has been defined. That program includes two main parts, the goal of the first one is to constitute a reliable experimental data base which allow the application of the existing models in this domain. The assessment of the ability of that models to describe the studied mechanical consequences is the objective of the second part. The test results and their numerical simulations presented in this paper show the necessity to take into account accurately the behaviour of the material.

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