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# Thermo-metallo-mechanical modeling of case-hardened steel parts for prediction of distortions during intermittent gas quenching

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## Abstract

Prediction of the residual distortions induced by quenching requires determining the thermomechanical properties of the material at different stages of the process. For case-hardened steels, with the appearance of a phase transformation, the impact of the phases must be taken into account, as well as the impact of the carbon content gradient. To develop a behavior model, properties such as Young's modulus, viscous stress, kinematic hardening, isotropic hardening, yield strength and transformation-induced plasticity parameter (TRIP) for austenite and martensite were determined using a specially developed experimental set-up.

## Introduction

The aeronautical industry is developing turbofan engines with high bypass ratios to increase efficiency. This requires the use of reduction gearboxes whose role is to lower the rotation speed of the fan in relation to the rotation speed of the turbine. These gearboxes transmit high power. These systems are made up of large gears that require perfect geometric quality and functional surfaces with very high mechanical properties. Case-hardened martensitic steels provide a good solution to this specific application.

The steel investigated is M50NiL or 13MoCrNiV42-16-14 grade. Its composition (Table 1) [1] was developed to ensure high toughness. Its low carbon content (0.13%) also prevents the formation of eutectic carbides during solidification. The addition of nickel, and therefore the stabilization of the austenitic phase, also compensates for the loss of hardenability caused by the lower carbon content.

C	Mn	Si	Cr	Ni	Mo	V
0,13	0,25	0,25	4,20	3,40	4,25	1,20

*Table 1: Nominal chemical composition of M50NiL steel (weight %)*

In our case, the parts are case-hardened and then heat-treated by gas quenching, cryogenic treatment and several tempering. This treatment, provides the expected properties, but causes geometric distortions of the functional surfaces, mainly during quenching.

Therefore, the industry needs are to understand and anticipate these distortions through numerical modeling. Academic studies have addressed internal stresses genesis during martensitic quenching and their consequences on distortions and residual stresses; the phenomenon is fairly well understood [2], [3]. While, models for the quantitative prediction of stress states and distortions have been developed by various research teams, models able to accurately predict distortion for complex parts and complex cooling path are much rarer.

The objective of this study is to develop a model describing stress and strain evolutions during heat treatment. This model must take into account the effect of the composition gradient on the metallurgical mechanisms, in particular martensitic transformations and related phenomena like transformation plasticity, retained austenite stabilization and self-tempering. The approach first involves characterizing the thermomechanical and metallurgical behavior of the material. Then, behavior laws will be proposed to describe the overall metallurgical and mechanical behavior of the steel during quenching.

## Experimental approach

A specific experimental set-up (Figure 1) was developed to determine martensite and austenite behavior laws, across the heat treatment temperature range (from 1090°C to -75°C) and for the various carbon contents involved in case hardening (from 0.13% to 0.8%).

The device simulates the heat treatment conditions. It consists of an induction heating system and a compressed air cooling system. Argon flow minimizes oxidation and decarburization. An electrohydraulic testing machine applies and controls loads and deformations at selected rates.

The thermo-elastoviscoplastic behavior of each phase (martensite/bainite and austenite) is identified through various isothermal mechanical tests carried out in the temperature range where these phases exist independently. The behavior is then extrapolated where the phases coexist. In this context, specimens with homogeneous carbon enrichment are used to evaluate the effect of the composition gradient and the properties throughout the depth of the cemented layer. Specifically, during these characterization tests (Figure 2), the specimen is austenitized under industrial conditions, to produce a full austenitic phase with initial characteristics (austenite grain size, chemical homogeneity, dissolution of carbides) similar to the industrial part. Cooling is subsequently performed and stopped at the desired characterization temperature (550°C in Figure 2).

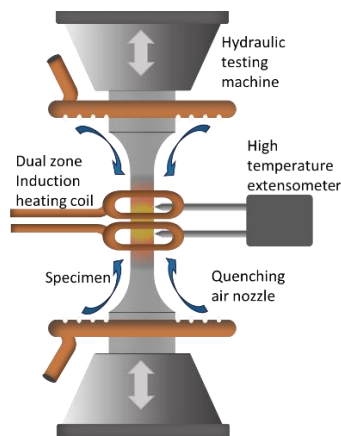


Figure 1: Diagram of the experimental set-up

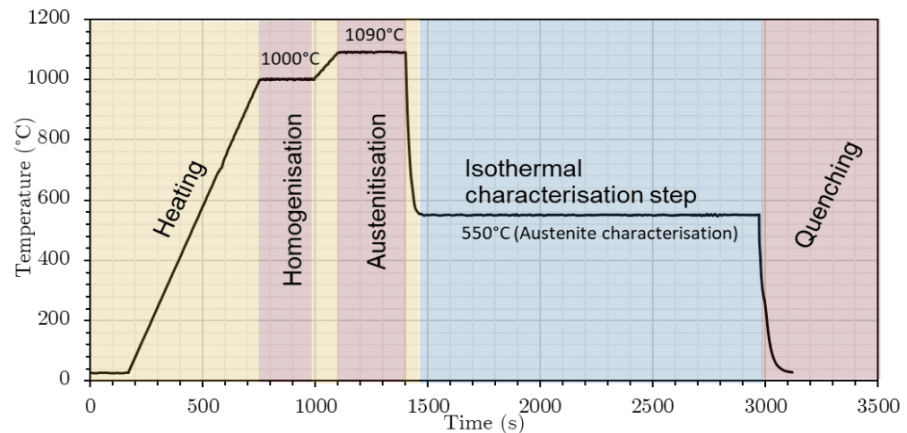


Figure 2: Example of a thermal cycle performed on the hydraulic testing machine (shown in fig.1) for a thermomechanical characterisation test of the austenite (here at 550°C).

During this isothermal interruption, a set of mechanical tests are carried out (Illustration Figure 3). First, a tensile load is applied at a constant strain rate to identify the Young modulus and yield strength. The strain rate is then increased to reveal the viscous behavior (strain rate sensitivity). Following this, a relaxation phase is then conducted by maintaining the strain which is used to identify the material's viscosity. The relaxation test offers a wide range of strain rates (from  $10^{-3} \text{ s}^{-1}$  to slow rates of around  $10^{-8} \text{ s}^{-1}$ ). The test concludes with cyclic loadings (tension/compression) at a constant strain rate. This cyclic strain-hardening test is used to identify kinematic component and isotropic component.

The aim is to carry out this testing sequence for each of the two phases. For austenite, the experimental plan includes tests conducted at 9 different temperatures in the austenitic range (1050°C, 1000°C, 900°C, 800°C, 700°C, 600°C, 500°C, 400°C, 370°C). To evaluate the effect of carbon content, these tests are repeated on multiple batches of specimens with carbon compositions representative of the carburized layer (0.13%, 0.4%, 0.6% and 0.8%).

For martensite, characterization of its thermo-mechanical behavior follows a similar approach, i.e., testing at several temperatures for different compositions. However, achieving a fully martensitic microstructure throughout the sample requires prior heat treatment (quenching and cryogenic treatment) conducted outside the characterization device. The tests are then performed isothermally, after controlled and interrupted reheating of the specimen on the testing machine. The experimental plan includes tests at 4 different temperatures (20°C, 100°C, 250°C, 350°C). To examine the effect of carbon content, the martensite characterization tests are repeated in the same manner as for the austenite using specimen with identical carbon compositions (0.13%, 0.4%, 0.6% and 0.8%).

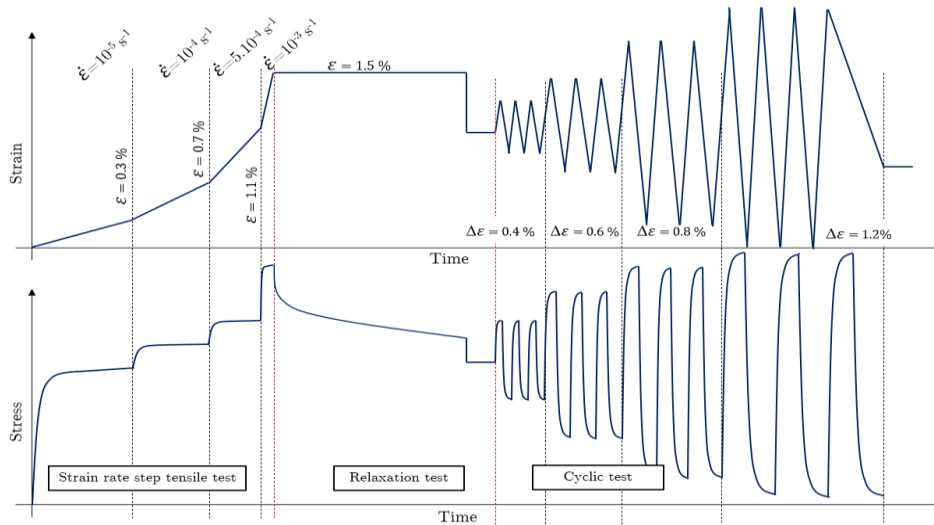


Figure 3: Schematic illustration of a thermomechanical characterization test.

Additional characterization is carried out using dilatometry tests on the same experimental set-up. The tests involve monitoring the dimensional changes of specimens during thermal austenitization and quenching cycles. This method provides information on transformation kinetics, start and end transformation temperatures and thermal expansion coefficients for each phase.

The dilatometry experimental plan includes quenching tests (continuous cooling from 1090°C to 20 °C or -75°C) for various carbon contents (0.13%, 0.4%, 0.6% and 0.8%) and cooling rates (50°C/s, 5°C/s, 0.5°C/s). Variations in cooling rate reveal the effects of self-tempering or austenite stabilization. These phenomena can influence transformation temperatures and kinetics [4-9]. Dilatometry tests under external loading are also planned to identify the transformation-induced plasticity effect. Tests with isothermal interruption (TTT) are also planned in order to identify and characterize potential phase transformations above martensite start temperature, particularly the bainitic transformation. Similarly to the phenomena of self-tempering and stabilization, a bainitic transformation prior to the martensitic transformation will have an impact on transformation temperature and kinetics [7], [10-12]. These tests will be supplemented by phase ratios quantification after treatment (using X-ray diffraction, electron and optical microscopy).

### Thermo-metallo-mechanical modeling

A global behavior model was developed to predict the distortions resulting from the quenching process. The model, inspired by the work of Roux [13], assumes a material composed of two phases, austenite (the parent phase) and martensite (the daughter phase). The volume fractions and properties change throughout the heat treatment. The mechanical response of the material during quenching is governed by the local response of the two phases. Assuming small perturbations, the total strain is expressed as an additive decomposition of various contributions: elastic strain, thermal strain, viscoplastic strain, strain due to volume change from phase transformation and transformation induced plasticity strain (TRIP). For the two-phase material, the same decomposition is introduced for each phase.

A self-consistent scheme as proposed by Kröner [14] is employed to incorporate the behavior of these two phases into the calculation. The approach models the mechanical state of each phase in the heterogeneous medium as equivalent to that of a spherical inclusion in an isotropic, infinite homogeneous medium based on the Eshelby inclusion [15]. The properties of the equivalent homogeneous medium are determined using a volume-weighted mixture law.

The thermomechanical behavior model also incorporates metallurgical mechanisms to describe the evolution of the phase fractions during quenching. The Koistinen & Marburger equation [16] is currently used to describe the progress of the martensitic transformation as a function of temperature. This equation depends on coefficients experimentally determined (including  $M_s$  the temperature at which the martensitic transformation starts and a kinetic parameter).

## Results and Discussions

A part of the characterization work focuses on the evolution of phase fractions during cooling. Figure 4 shows the results of rapid quench dilatometry tests conducted at 50°C/s. The tests were carried out on M50NiL specimens in the as-received condition and on specimens enriched with 0.8% carbon by mass.

These curves show a drop in austenitization temperatures, with Ac1 dropping from 780°C at 0.13% carbon to 720°C at 0.8% carbon. Additionally, the enriched sample exhibits faster Austenitisation kinetics.

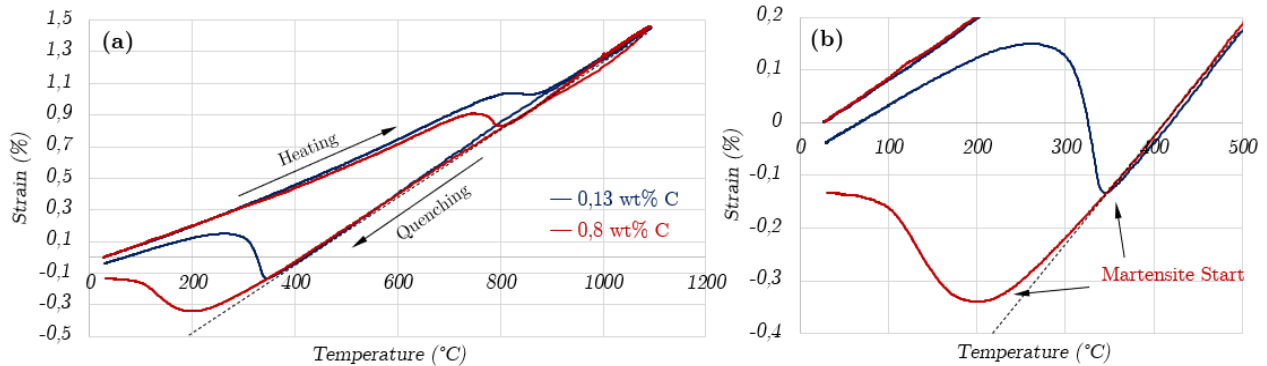


Figure 4: Dilatometric curves for rapid quenching (50°C/s) carried out on the thermomechanical device for a specimen not enriched with carbon (0.13 wt% carbon) and for an enriched specimen (0.8 wt%). (a) Full treatment curves, (b) Detail of martensitic transformation expansion)

In agreement with the literature [17], the Ms temperature is significantly reduced by the addition of carbon. It decreasing from 365°C to 250°C for the sample with 0.8% carbon. The martensitic transformation kinetics are also slowed for the enriched sample, with a change in the transformation rate at around 120°C, followed by an additional slowdown. We also note that for this enriched sample, the transformation does not appear to be complete at room temperature, requiring further cooling to cryogenic levels to achieve full transformation.

Figure 5 shows the preliminary results of the thermomechanical characterisation of austenite at high temperature. These curves show the results of tensile tests with strain rate jumps at 700°C, 800°C, 900°C and 1000°C. As the temperature increases, the yield strength decreases significantly, of 65 MPa at 700°C and 18 MPa at 1000°C. At 900°C and 1000°C, the strain rate sensitivity appears to increase with temperature. In contrast, at 700°C and 800°C, the strain rate sensitivity appears to be very low. However, as shown in figure 6 with an example of austenite relaxation tests at 800°C, the stress decreases significantly and rapidly when the strain level is maintained. A similar phenomenon is also observed at 700°C.

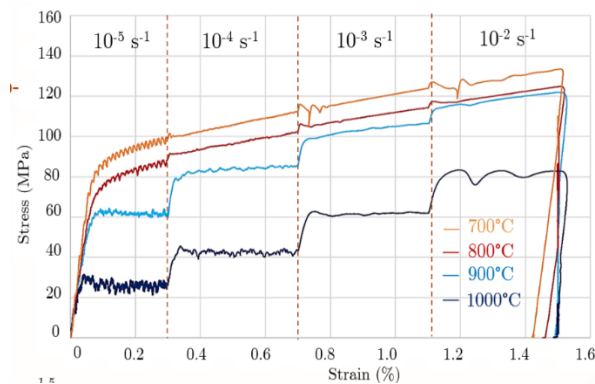


Figure 5: Viscosity and plasticity test results for austenite (at 700°C, 800°C, 900°C and 1000°C) established using tensile tests with a strain rate step.

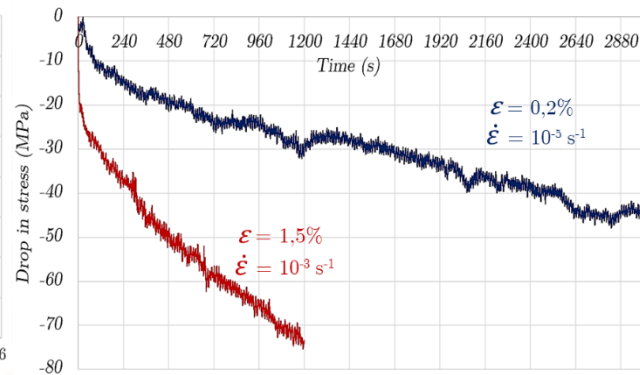


Figure 6: Results of austenite relaxation tests at 800°C for two different initial deformations:

Free dilatometry tests at the same temperatures are conducted out in parallel with these thermomechanical tests to confirm that no phase transformation occurs during characterization and that only austenite is present.

## Conclusions

The experimental set-up developed for this study gives promising initial results. The first experiments demonstrate that it is possible to gain reliable and repeatable access to the overall behavior of austenite as a function of temperature. These initial findings reveal complex behavior for the austenite, with significant variations as a function of temperature, particularly for the viscous effect.

The device also proves its capacity as a dilatometer, with successful initial experiments in free dilatometry (and under stress) during martensitic quenching. In this context, the results show good repeatability and values very close to those found in the literature.

Model parameters are currently being identified for unenriched steel, and the first calculations on homogeneous volume elements will be carried out shortly.

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