ULTRA-HIGH DUCTILITY OF TRIP-ASSISTED STEELS MODELLED BY GRADIENT PLASTICITY

Mahdi K. Hatami [1], Thomas Pardoen[2], Gauthier Lacroix [2], Peter Z. Berke [1], Pascal J. Jacques [2], Thierry J. Massart [1a)]
[1]*BATir Department, Université libre de Bruxelles (ULB), Brussels, Belgium*
[2]*Institute of Mechanics, Materials and Civil Engineering, Université catholique de Louvain, Louvain-La-Neuve, Belgium*

Summary TRansformation Induced Plasticity (TRIP) is an attractive route to increase the strain hardening capacity of steels containing a fraction of metastable austenite, leading to higher strength and uniform elongation. In spite of performances reached in the past decades, microstructure optimization is complex due to the interplay of coupled effects on the transformation kinetics and work hardening (phase stability, size of austenite grains, temperature and loading path). An averaging scheme is developed for predicting the response of TRIP-aided multiphase steels using strain gradient plasticity. The model parameters, based on transformation kinetics, are identified based on experimental results at different temperatures. Classical plasticity cannot capture the TRIP effect on the mechanical response, while strain gradient plasticity predicts the variation of strain hardening with deformation and temperature, paving the way towards microstructure optimization.

INTRODUCTION

Over the last decades, the demand for steels with enhanced hardening capacity, led to the manufacturing of various TRIP (TRansformation Induced Plasticity) assisted multiphase steels [1]. Transformation induced plasticity is an efficient strategy to obtain superior strength/ductility balance, by raising the strain hardening capacity through the continuous transformation along deformation of a fraction of metastable austenite retained thanks to specific metallurgical treatments. By varying the composition and processing route, the volume fraction, stability, size and initial strength of retained austenite can be controlled, leading to different transformation kinetics and plastic behavior [1]. The size-dependent response in TRIP steels was considered in [2], showing that strain gradient plasticity (SGP) effects associated to the phase transformation can have a first order effect, as the transformation occurs in regions in the range of 1μm. This model revealed strong effects related to plastic strain gradients on the TRIP mechanism. However, unit cells representing only one grain were considered, preventing a qualitative reproduction of experimentally observed trends. Here, this approach is extended to allow direct comparison with experimental data. This requires addressing representative volume elements rich enough to encompass a large number of austenite grains transforming at different levels of deformation.

HOMOGENIZATION PROCEDURE

The behaviour of each phase is described by the Fleck-Hutchinson gradient plasticity theory [3], in which the effective plastic strain is generalized, incorporating plastic strain gradients within a term that accounts for geometrically necessary dislocations (GNDs). A 2D plane stress element is used, with higher-order boundary conditions on the plastic strain field, applied at the boundary of the appearing martensitic phase, with a vanishing plastic flow upon transformation.

A simplified 2D unit cell, containing a circular austenitic inclusion within a ferritic matrix, is used, see Fig. 1. Upon loading, the austenitic inclusion partially transforms into a martensitic phase. The phases volume fractions are based on experimental data [4]. The unit cell is embedded in a surrounding medium to iso-strain or iso-stress transformation conditions. The mechanical influence of the transformation on the unit cell average behavior is examined, assuming that the final volume fraction of the martensitic phase appears at once with evolving material properties. This is achieved in three stages: (i) the material is subjected to the loading conditions until a specific average unit cell strain level, (ii) the material properties of the elliptical zone are updated gradually from the austenite to the martensite properties, with the external loading temporarily stopped and with a transformation eigenstrain imposed to the appearing martensitic phase, (iii) the mechanical loading is resumed after the transformation.

In order to capture the global response of the TRIP steel corresponding to experimentally observed heterogeneous transformation kinetics, one should account for the fact that a variant of austenite transforms fast and not progressively, but that different austenite grains transform at different deformation levels. An averaging procedure is used in which the overall material is represented by several unit cells, assuming that each can be simulated independently. The experimental transformation kinetics is exploited to identify the distribution of macroscopic strain levels at which the transformation initiates. The transformation kinetics is therefore discretized, providing a set of macroscopic strain levels at which transformations start. For a given kinetics, a set of unit cells thus predicts the local behavior for different starts of transformation. After computing individual unit cell responses corresponding to different transformation initiation strains (Fig.1), they are recombined by means of a weighted sum to evaluate the global material behavior. An equal weighting factor is imposed here on each unit cell. As a result of the use of a finite number of unit cells, the global material response exhibits an oscillatory pattern as depicted in Fig. 1 that requires subsequent smoothing.

[a)] Corresponding author. Email: thmassar@ulb.ac.be

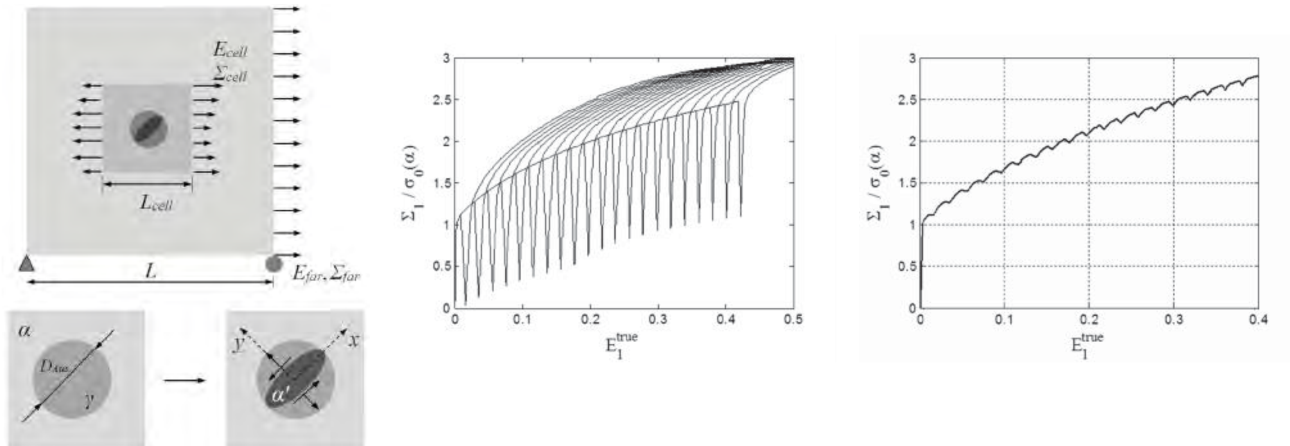

Fig. 1. (left) unit cell and embedded cell to model transformation without average stress or strain control, (center) set of unit cell responses with increasing strains at transformation according to experimental kinetics, (right) resulting average stress-strain response.

SIMULATION OF ISOTHERMAL TENSILE DEFORMATION TESTS

Using parameters reported in [4], the model allows semi-qualitatively reproducing experimentally observed results. Hardening laws are adjusted to reproduce the results corresponding to an isothermal tensile test at 80°C, as shown in Figure 2 for material parameters in the range used in [5]. The internal length is selected as the one allowing the best agreement with experimental results at this temperature. Using this set of parameters, corresponding to a SGP intrinsic length scale l_*/D_{aust} = 0.75, the drop of ductility observed for faster kinetics observed at lower temperatures can be captured by the SGP model. The classical plasticity model, on the contrary, cannot capture any significant drop in the strain at necking, see Fig 2. A similar qualitative agreement can also be shown for non-isothermal tensile conditions with more complex kinetics.

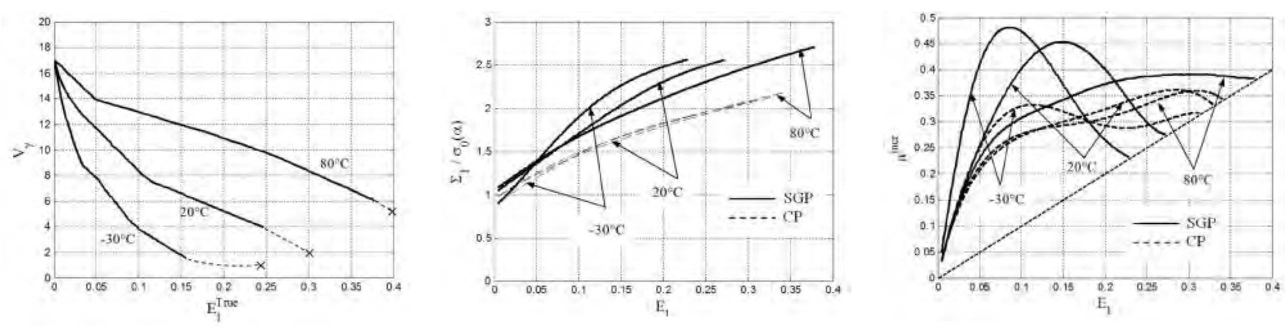

Fig. 2. (left) Experimental transformation kinetics (evolution of austenite volume fraction during straining) for isothermal tests [4], (center) Stress-strain response for Strain Gradient (SGP) and Classical (CP) Plasticity, (right) Considere plot for necking detection.

CONCLUSIONS

A comparison of the size dependent results with the trends obtained with a classical plasticity shows that a size dependent framework is a key feature in order to capture the effect of the transformation kinetics on the overall material behavior of TRIP assisted steels. Based on experimentally identified material parameters, the computational results agree well with the experiments in terms of the prediction of the ductility as a function of the transformation kinetics. Future works will focus on the means to generate refined microstructures, and on the practical generation of microstructures exhibiting tailored transformation kinetics towards optimized ductility of TRIP assisted steels.

References

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