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FE determination of the plasticity induced during diffusive transformation in the case of nucleation at random locations and instants

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Abstract

The evolution of TRansformation Induced Plasticity (TRIP) in a steel where the parent phase has been strain-hardened, for a martensitic as well as a bainitic transformation, can only be predicted with models taking into account the interaction between classical plasticity and TRIP. One of the most famous, due to Leblond [J.B. Leblond, Int. J. Plasticity 5 (1989) 573–591], does not provide satisfying predictions in the experimental cases of pre-hardening explored by Taleb and Petit-Grostabussiat [L. Taleb, S. Petit-Grostabussiat, J. Phys. IV 12 (2002) Pr11–187–194; L. Taleb, S. Petit, Int. J. Plasticity 22 (2006) 110–130]. This has motivated the development of alternative approaches based on Finite Element (FE) analysis, which calculates equilibrium at the local scale of the interaction between phases without adopting any particular assumption on stress and strain fields. Our studies concern in particular diffusional transformation where the last improvement has consisted in introducing a new law to govern the kinetics of nucleation: whereas previous works were based on the assumption of site saturation (instantaneous nucleation), it is considered here that nucleation happens randomly in space as well as in time, with a controlled probability distribution and evolution in time.

Keywords: Transformation plasticity; Micromechanical modelling; Finite elements; Diffusive transformation

1. Introduction

The transformation plasticity phenomenon appears when a solid phase, usually a metal, is subjected to a phase transformation (austenitic phase γ is transformed into bainitic phase α, for example) under an external stress which is lower than the yield stresses of the constituents. During the transformation, the difference in the mechanical properties of the phases α and γ generates internal stresses which, under external loading, cause a microscopic plasticity in phase α mostly. These plastic strains induced by transformation correspond to the so-called TRIP (TRansformation Induced Plasticity) on the scale of a bulk material. From the microstructural point of view, there are two mechanisms which can explain this phenomenon: mechanism of Magee [4] and that of Greenwood–Johnson [5]. The Magee's mechanism relates to the development of martensite in the form of plates while that of Greenwood–Johnson [5] is dominating in diffusional transformation. According to this mechanism, the TRIP is due to the difference of compactness between parent and product phases: this difference generates microplasticity in microareas which is channeled in the direction of the external load.

There are several authors who have proposed their modelling associated with transformation plasticity. One will generally note that for many of them, only the Greenwood–Johnson's mechanism [5] is considered. The most famous model which allows to account for the effect of austenite pre-hardening on the transformation plasticity is Leblond's model [1]. Still, it has been shown in Taleb and

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Grostabussiat's works [2,3] that the TRIP predictions from the Leblond model were significantly different from the experimental observations, especially in the case of the martensitic transformation: for example, a pre-hardening in tension has led to a significant positive TRIP (in the direction of tension) whereas the Leblond model predicts either a null or a negative TRIP according to the type of hardening (isotropic or kinematic). This observation has motivated the development of an alternative approach of modelling where as few as possible assumptions are made concerning the stress and strain fields in the medium subjected to phase transformation. Finite elements are used to describe arbitrarily the evolution of the microstructure of a volume element – large enough for its apparent properties to be representative of a macroscopic volume – during the transformation and to compute the stress and strain fields resulting from the mechanical interaction between phases combined to an external load.

It has to be noted that, first attempts have been made, in the work of Benke [6], to couple a three-dimensional phase field modelling to a FE code; the aim is to compute the driving force by taking into account elastic as well as viscoplastic interactions between phases. This approach allows to compute the local stress and strain fields during a transformation whose kinetics are not arbitrarily controlled as in the present work. However, because phase field modelling consists in describing locally the evolution of the concentration of atomic or molecular species (scale of a grain boundary typically), it requires a very fine discretization in space and time; so, for a given domain of investigation, it calls on much more numerical operations than FE analysis dedicated to the modelling of a global behavior (scale of several tens or hundreds of grains). Hence, with the current performances of computers, the coupling of phase field modelling and FE is restricted to domains containing very few nuclei; any perspective of computing the TRIP in a representative volume element (containing a large number of nuclei as explained in [7]) is prohibited.

Some preliminary investigations, on the basis of the Ganghoffer's numerical modelling [8], have been presented in previous works:

- In the basic configuration, developed and analyzed in details in [9], a single nucleus at the centre of a cubic cell is considered; this corresponds to the case where nuclei appear instantaneously according to a spatial cubic array and start to grow at the same instant, with a same rate.
- The restricting assumption on the spatial distribution of nuclei is generalized to the case of random positions in [10,7], appearing also instantaneously, as in the case of site-saturation.

The present work proposes an extension of these modellings to the case of nuclei appearing randomly in space as in time, with a uniform probability which is controlled according to the volume fraction of product phase. First, the modelling is described in Section 2, divided into two subsections, 2.1 for the FE characteristics and 2.2 for the kinetics. Then, the kinetics provided by the numerical modelling is analyzed in Section 3, before paying attention to results in terms of TRIP in Section 4.

2. Modelling

2.1. FE modelling

2.1.1. Volume of investigation

The aim is to characterize the effective behavior of a representative volume element, more particularly the evolution of TRIP as a function of the product phase volume fraction. According to the way effective properties of polycrystals are determined from FE computations (see, among other examples [11,12]), it is possible to (i) subdivide the medium into Voronoi polyhedra – the grains, (ii) to construct a mesh which respects the tessellation and (iii) to attribute elastoplastic crystalline constitutive laws to each grain. But for the moment, the parameters describing austenite crystal plasticity have not been determined. For this main reason and because this work is only a step towards a more physically consistent ground, we have adopted the same hypothesis as classical TRIP micromechanical models: each phase has homogeneous elastoplastic properties.

2.1.2. Behavior

The parameters for bainitic transformation have been determined from experimental measurements of Taleb and Sophie Grostabussiat on a 16MND5 steel [13,14]. They are reported in Table 1 with R_0, H and ε_{tr} being, respectively, the yield stress, the hardening coefficient in the case of linear hardening and the transformation strain (isotropic dilation), defined in Eq. (1). Though mechanisms of bainite formation are not exclusively diffusional (displacive or martensitic transformation also intervenes), as in Greenwood–Johnson based micromechanical models, only the diffusional part of the transformation is considered in the modelling. In this work, linear isotropic hardening is chosen. Previous investigations have shown that the type of hardening (isotropic or kinematic) could have an effect all the more important than pre-hardening were involved in the TRIP test. The question as to how this choice of the type of hardening would affect our TRIP results is not under consideration in this paper.

Table 1
Material properties chosen for bainitic transformation

	E (MPa)	ν	R_0 (MPa)	H (MPa)	ε_{tr}
Austenite	160,000	0.3	107	2800	–
Bainite	160,000	0.3	433	4500	0.0055

They are taken from the experimental investigations of [13,14]. R_0 is the yield stress, H is the modulus of linear isotropic hardening and ε_{tr} is the dilatational transformation strain.