International Journal of Plasticity 81 (2016) 18–39

Contents lists available at ScienceDirect

International Journal of Plasticity

journal homepage: www.elsevier.com/locate/ijplas

Periodic homogenization for fully coupled thermomechanical modeling of dissipative generalized standard materials

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ARTICLE INFO

Article history:
Received 11 September 2015
Received in revised form 20 January 2016
Available online 8 February 2016

Keywords:
A. Thermomechanical processes
B. Elastic-viscoplastic material
B. Layered material
C. Asymptotic analysis
Periodic homogenization

ABSTRACT

The current work deals with periodic thermomechanical composite media, in which the material constituents are considered to obey the generalized standard materials laws. The aim is to provide a proper homogenization framework that takes into account both the equilibrium and the thermodynamics laws in microscale and macroscale levels. The study is based on the asymptotic expansion homogenization technique, which permits to deduce useful results about the general structure of microscale and macroscale energy potentials and constitutive laws. The paper also proposes an incremental, linearized formulation that allows to identify suitable thermomechanical tangent moduli for the macroscale problem. The capabilities of this framework are illustrated with numerical examples on multilayered composites.

1. Introduction

The recent advances of the materials science and the increased needs of many engineering applications has led to the tremendous growth of composite materials. The automotive and aerospace industry require smart composites that are able to be utilized in complicated structures with high demands in strength, multifunctionality and durability, and at the same time to have long lifetime during repeated loading cycles.

To match those high requirements, composite materials are often utilized in regimes where dissipative phenomena occur, i.e viscoelasticity, viscoplasticity, plasticity or phase transformation. Such mechanisms may be accompanied by a significant temperature change, which influences in return the material behavior. To account for such thermomechanical coupling is especially important in the case of polymers being utilized in temperature ranges close to the glass transition zones, or in shape memory alloys, and is a key feature to accurately predict fatigue in composite materials (Benaarbia et al., 2015).

Such strong couplings have been already taken into account in the constitutive equations, e.g. in the generalized standard material definition (Germain, 1973; Halphen and Nguyen, 1975; Germain, 1982; Germain et al., 1983). However, in the case of composite materials, very few works have been dedicated to the study of the fully coupled thermomechanical behavior of composites. This topic is nowadays of a great importance since, for instance, fatigue of composites is a complicated mechanism that depends not only on the stress state, but also on the energy dissipation that occurs during inelastic mechanisms.

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http://dx.doi.org/10.1016/j.ijplas.2016.01.013
0749-6419/

Thus, an appropriate study of the fatigue of a structure requires to consider the energy exchanges during thermomechanical loading cycles.

The scope of the current manuscript is to identify, through the asymptotic expansion method, a proper, fully coupled, thermomechanical homogenization framework for the study of periodic composites consisting of generalized standard materials. The response of generalized standard materials is properly described by a set of suitable state and internal variables. Thermodynamic forces related with these variables can be obtained through the definition of a free energy potential. Additionally, the introduction of a dissipation potential allows to define evolution equations for the internal variables from the dissipation inequality. In composites, the dissipation inequality should be satisfied in both micro and macro levels in order to lead to accurate constitutive evolution equations for the internal variables.

Modeling the mechanical behavior of heterogeneous, nonlinear, dissipative composite materials has been the subject of many researchers. Several multiscale techniques have been proposed in order to identify the overall behavior of viscoelastic, elastoplastic, viscoplastic, or damaged composite materials (Suquet, 1987; Ponte-Castañeda, 1991; Terada and Kikuchi, 2001; Desrumaux et al., 2001; Meraghni et al., 2002; Yu and Fish, 2002; Aboudi et al., 2003; Aboudi, 2004; Chaboche et al., 2005; Love and Batra, 2006; Asada and Ohno, 2007; Jendli et al., 2009; Mercier and Molinari, 2009; Khatam and Pindera, 2010; Cavalcante et al., 2009; Kruch and Chaboche, 2011; Brenner and Suquet, 2013; Tu and Pindera, 2014; Cavalcante and Pindera, 2016). Review papers discussing the various multiscale approaches have been written by Pindera et al. (2009); Charalambakis (2010); Mercier et al. (2012).

In the homogenization theories for generalized standard materials with nonlinear dissipative mechanisms there is no general and unique way to express the two potentials (Helmholtz or Gibbs and the dissipation potential) for the macroscopic composite behavior. Many proposed methodologies in the literature overcome this difficulty by assuming specific form of the macroscopic response and then obtain the correlation with the microscopic variables (Hutchinson, 1976; Sun and Ju, 2004; Suquet, 2012). Moreover, these works focus exclusively on the mechanical behavior, ignoring the effects of the mechanical work in the energy balance. Fully coupled thermomechanical study for composites under large deformation processes with arbitrary choice of constituents constitutive laws has been performed recently by Sengupta et al. (2012). This work presents original and interesting results, but it is based on certain assumptions about the form of the conservation laws in both scales and the correlation between microscopic and macroscopic variables. Also, no discussion about the thermodynamic micro- and macro-energy potentials is provided.

The asymptotic expansion homogenization method has been developed for periodic media and its advantage is that it does not require initial assumption about the form of the microscopic and macroscopic equations that describe the problem under investigation. It starts with a general form of the system of equations, and through appropriate asymptotic expansions on the field variables (displacement, temperature e.t.c.) identifies rigorously how this system is represented in microscale and macroscale (Bensoussan et al., 1978; Sanchez-Palencia, 1978). Nowadays this method is considered classical and fairly straight forward regarding the case of thermoelastic media. In the case of inelastic mechanisms of plasticity type, it has been implemented successfully (see for instance Fish et al., 1997 for composites with plasticity type strains and Herzog and Jacquet, 2007 for shape memory alloy composites), but no discussion about the influence of mechanical dissipation on the temperature of the composite appears in these works. Only a limited number of studies have considered fully coupled thermomechanical processes by combining the conservations of linear momentum and energy (Ene, 1983; Yu and Fish, 2002; Temizer, 2012). Yu and Fish (2002), using the asymptotic expansion homogenization framework, have performed a fully coupled thermomechanical analysis for viscoelastic periodic composites. Their analysis though is based on specific type of constitutive law and the proposed methodology cannot be applied in the same way for other type of inelastic materials.

The novelty and originality of the present work is that it presents a fully coupled thermomechanical homogenization framework under small deformation processes, without considering apriori any specific type of constitutive law, allowing different types of inelastic material behaviors for the various constituents of the composite. The developed methodology identifies initially the micro and macro conservation laws (equilibrium, thermodynamics), and investigates afterwards how a general energy potential (for instance Helmholtz or Gibbs), or more accurately its rate, is properly formulated in both scales. While the tool utilized in this analysis (the asymptotic expansion method) is considered rather classical, to the best of the authors knowledge such type of general investigation has never been performed in the literature. The outcome of this study is that it proves in a systematic and consistent manner which variables and equations in the fully coupled thermomechanical problem can be rigorously identified in the macroscopic scale and which variables require either additional assumptions or numerical treatment (as it is performed here with the linearized incremental formulation).

This paper attempts a systematic study of the homogenization of periodic composites under fully coupled thermomechanical loading conditions. The asymptotic expansion homogenization method is employed in Section 2 in order to identify in both micro and macroscale a) the form of the conservation laws (equilibrium, first and second thermodynamic laws) and b) the energy potentials of generalized standard materials, the mechanical dissipation and the connection between the various thermomechanical fields. Section 3 presents a computational scheme based on a linearized incremental form, which allows to obtain numerically macroscopic thermomechanical tangent moduli. A general discussion about the homogenization approach results is provided in Section 4. Section 5 presents some illustrative examples on multilayered composites using the proposed framework. The paper is also accompanied by a conclusion section and one appendix.