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Average phase stress concentrations in multiphase metal matrix composites under compressive loading

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ABSTRACT

We develop a model to predict average over individual phases stress concentrations in a multiphase metal matrix composite under compressive loading. The model accounts for matrix plasticity through variation of the shear modulus with applied stress and for fracture of filler through change in the shape of the particles. Three micromechanical models are compared – non interaction approximation, Mori–Tanaka–Benveniste (MTB) scheme, and Maxwell scheme. Comparison with the experimental measurements of Cabeza et al. (2016) shows that Maxwell scheme generally predicts the stress concentration with satisfactory accuracy. Results of MTB scheme vary depending on the loading case and ignoring of the interaction leads to substantial overestimation of the stresses.

1. Introduction

In the present paper, we develop a micromechanical model for average stress fields in a multiphase metal matrix composite accounting for interaction between the inhomogeneities, matrix plasticity and fragmentation of the fibers. The theoretical results are verified with experimental data of Cabeza, Mishurova, Bruno, Garcés, and Requena (2016) on AlSi12CuMgNi alloy reinforced with alumina fibers. Its microstructure is illustrated in Fig. 1. Needle-like alumina fibers are random oriented within the plane section, while some sporadic fibers are out of plane (in dark contrast in Fig. 1a and soft grey in Fig. 1b). The fibers seem to be homogenously distributed within the soft grey aluminum matrix. Eutectic Si phase presents a lamellae structure (grey and dark grey for Fig. 1a,b respectively), while intermetallic particles are globular (grey and bright contrast for Fig. 1a,b, respectively).

Aluminum matrix composites represent an important class of materials, which was originally designed to merge the ductility of metals with the stiffness of ceramics (Ashby, 1999). Indeed, they have shown promising mechanical properties: improved stiffness and strength, with respect to the unreinforced alloy. Their application has however not yet penetrated the markets it was intended for (automotive and aeronautical), because of the loss of ductility due to the introduction of a ceramic reinforcement. This poor ductility has also the consequence that by static loading, the maximum strain at rupture is drastically reduced.

A way to overcome the problem has been found taking inspiration from the precipitation-strengthened alloys. The modern trend to guarantee minimum ductility requirements is to induce precipitation of a eutectic phase (Lasagni & Degischer, 2010; Lasagni, Acuna, & Degischer, 2008; Requena, Garcés, Rodrıguez, Pirling, & Cloetens, 2009). In particular, some Al alloys

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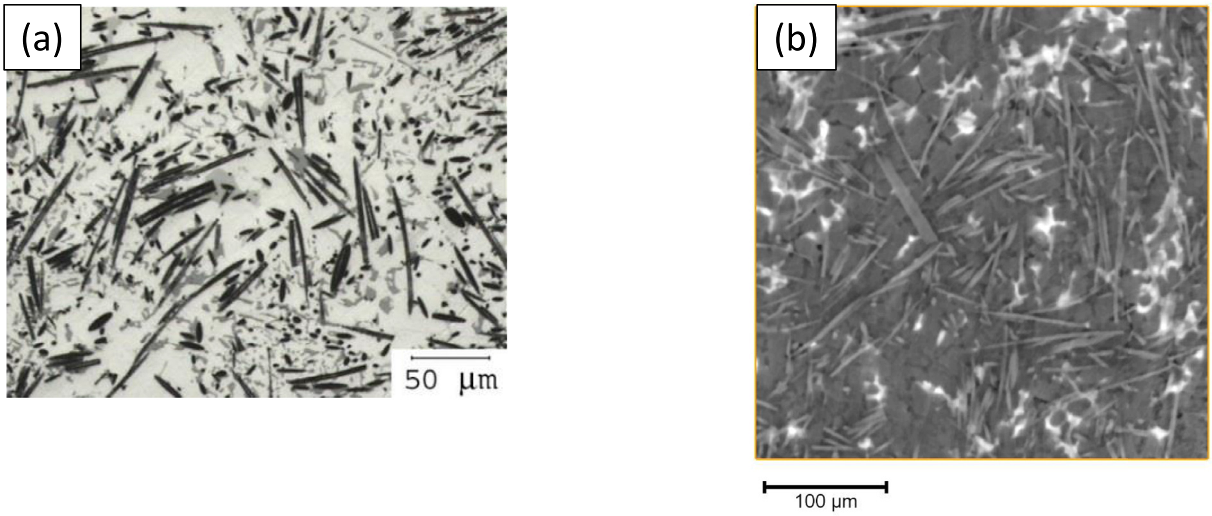

Fig. 1. AlSi12CuMgNi alloy reinforced with alumina fibers: (a) Optical microphotograph of a two-dimensional cross-section in the plane of fibers; (b) 2-D slice of reconstructed data in the plane of fibers from computed tomography (courtesy of Prof. G. Garcés, CENIM-CSIC, Madrid).

form a network of precipitates, which even in absence of ceramic reinforcement increase the mechanical properties of the matrix. Alloys such as Al12Si or Al7Si are indeed currently used in the automotive sector. Silicon precipitates may then form an interconnected network (Requena, Garcés, Rodrıguez, Pirling, Cloetens, 2009) in presence of reinforcement fibers, thereby playing the role of bridges during crack propagation. This further reinforcement mechanism allowed substantially improving certain mechanical properties (toughness).

This progress in materials design has been accompanied by a correspondent characterization effort, but not matched on the theoretical (modeling) side. While models exist for two-phase composites, very little has been undertaken for multi-phase materials. Indeed, for instance, Dlouhy, Merk, and Eggler (1993, 1995) proposed micromechanical explanation of creep of short fiber reinforced MMC. The damage in the form of fiber fragmentation under tension was observed and modeled by using a shear lag approach. The model is restricted to the case of a uniaxial loading of a composite reinforced with perfectly parallel fibers. Phase average stresses during compression and tension of metal matrix composites with 10–15 vol% of alumina short fibers have been studied by Garcés, Bruno, and Wanner (2007). The authors adopted a previously developed model of Wanner and Garcés (2004) for creep behavior and accounted for fibers damage using a heuristic function for effective Young's modulus of fibers. The model showed qualitative agreement with experimental measurements. However, it is applicable for two phase composites only (matrix reinforced with short fibers). The evolution of residual stresses in pre-strained specimens and in-situ during compression of two-phase composite was studied by Garces, Bruno, and Wanner (2006a) and (2006b), respectively. To model the loading process, authors used Eshelby (1957) results and treated elastic-perfectly plastic matrix using bilinear law.

Lasagni et al. (2008) and Lasagni and Degischer (2010) performed experimental and theoretical studies of elastic modulus for several Al-Si alloys with and without reinforcement. Results show that a continuous eutectic Si network contribute to the stiffness of the alloy and improve the Young's modulus for short fiber reinforced composite. Requena, Garcés, Danko, Pirling, Boller (2009) and Requena, Garcés, Rodrıguez, Pirling, Cloetens (2009) studied load partition during compressive loading in Al-Si alloys without fibers and reinforced with vol.20% of Al_2O_3 short fibers, respectively. In the case of AlSi12 alloy, eutectic Si structure carries a portion of applied load together with alumina fibers. The experimental results were supplemented by micromechanical modeling. The authors calculated the phase average strain concentration using non-interaction approximation and Mori–Tanaka effective field method.

To the best of our knowledge, the joint effect of the matrix plasticity, fragmentation of the inhomogeneities, and interaction between them has never been properly addressed in calculation of stress averages over phases (the strength of the interaction, in particular, has never been assessed). It can be done using effective field micromechanical models. Among them, Mori–Tanaka–Benveniste scheme (Benveniste, 1987; Mori & Tanaka, 1973) applied to anisotropic multiphase composites leads to physically inconsistent results (lose of symmetry of the effective compliance/stiffness tensor, Norris, 1989; Qiu & Weng, 1990). Kanaun-Levin scheme (Kanaun & Levin, 2008) requires physically questionable assumption that different phases are subjected to different effective fields (Kanaun & Jeulin, 2001). It appears that Maxwell scheme (Maxwell, 1873) treated as an effective field method does not produce any inconsistencies of the mentioned type. We compare the results obtained by Mori–Tanaka–Benveniste scheme and by Maxwell scheme. Changes in mechanical performance of the matrix and fragmentation of the inhomogeneities observed in experiments of Cabeza et al. (2016), are treated using approach proposed by Sevostianov and Kachanov (2015) through identification of a certain tracking parameter that tracks the evolution