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A multi-length scale sensitivity analysis for the control of texture-dependent properties in deformation processing

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Abstract

Material property evolution during processing is governed by the evolution of the underlying microstructure. We present an efficient technique for tailoring texture development and thus, optimizing properties in forming processes involving polycrystalline materials. The deformation process simulator allows simulation of texture formation using a continuum representation of the orientation distribution function. An efficient multi-scale sensitivity analysis technique is then introduced that allows computation of the sensitivity of microstructure field variables such as slip resistances and texture with respect to perturbations in macro-scale forming parameters such as forging rates, die shapes and preform shapes. These sensitivities are used within a gradient-based optimization framework for computational design of material property distribution during metal forming processes. Effectiveness of the developed computational scheme is demonstrated through computationally intensive examples that address control of properties such as Young's modulus, strength and magnetic hysteresis loss in finished products.

Keywords: Multi-scale modelling; Continuum sensitivity analysis; Polycrystal plasticity; Materials-by-design; Forming process design

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1. Introduction

Realization of optimal material properties is important to address the critical performance needs of hardware components in aerospace, naval and automotive applications. Newly emerging property design strategies for metallic materials are aimed towards tailoring microstructural subsystems by controlling processes that govern their evolution (Olson, 1997). An example is in composite design, where techniques that enable tailoring of microstructure topology have allowed identification of structures with interesting extremal properties such as negative thermal expansion (Sigmund and Torquato, 1996) and negative Poisson's ratio (Lakes, 2000). One such technique for optimizing properties of metallic materials, comprised of a polycrystalline microstructure, involves tailoring of preferred orientation of crystals manifested as the crystallographic texture. During forging and extrusion processes, mechanisms such as crystallographic slip and lattice rotation drive formation of texture and variability in property distributions in polycrystalline materials. A possible method for designing property distribution in such materials is to control the deformation so that textures with desired properties are obtained. Several applications exist where certain textures are desirable to improve properties of materials. For example, a Goss texture is desirable in transformer cores to reduce power losses during magnetization (Rollett et al., 2001). In deep drawing, a high value of texture-dependent R parameter (Hosford, 1993) and low planar anisotropy is necessary to prevent earing and to increase drawability of the sheet.

Recent developments in microstructure-sensitive design have addressed problems such as computing optimal textures that lead to desired properties from the space of all possible textures (Adams et al., 2001; Kalidindi et al., 2004). The problem of identification of processing paths that lead to such optimal textures is being addressed using novel means such as representation of processing paths in microstructure spaces using spectral (Li et al., 2005) or reduced order representations (Sundararaghavan and Zabaras, 2007) and using gradient optimization techniques (Acharjee and Zabaras, 2003; Sundararaghavan and Zabaras, 2006). However, the success of such process design techniques has only been demonstrated at the microstructural length scale. The novelty in this work is that process design is performed using two different length scales. The macro-scale is associated with the component being modelled (10^{-3}–10^{1} m) and the meso-scale is characterized by the underlying polycrystalline microstructure (10^{-6}–10^{-3} m). We address the design problem of computation of macro-scale parameters such as forging velocity, die and preform shapes such that microstructure evolution is tailored towards achieving desired properties.

The optimization problem involves minimizing an objective function that is an error measure between the desired property and the numerically calculated properties for a given set of macro-scale parameters. A sensitivity analysis scheme is used for calculating the gradient of the objective function and to drive the optimization procedure (Srikanth and Zabaras, 2001; Zabaras et al., 2003). Posed in a multi-scale sense, the approach is used to compute sensitivities of microstructural fields such as slip resistance, crystal orientations due to perturbations in macro-scale parameters. These sensitivities are exactly defined using a set of field equations developed by directly differentiating the governing equations with respect to small perturbations in the macro-scale process parameters. An averaging principle is then developed to compute sensitivity of stress and various material properties at the macroscopic level from microstructural sensitivity fields. Evolution of the micro-scale during forming is modelled using continuum representation of texture (Kumar