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EVOLVING HIGHER-ORDER BOUNDARY CONDITIONS IN STRAIN GRADIENT BASED ANALYSIS OF PLASTICITY IN HETEROGENEOUS MICROSTRUCTURES

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ABSTRACT

Classical plasticity theories do not account for the increase of hardening associated to a decrease of the size of the microstructural features typically in the micrometer range, e.g. in thin films mechanics or indentation [1]. Various phenomenological formulations have been developed to incorporate such effects, by introducing the effect of strain gradients in the constitutive setting. Among such theories, descriptions including higher order equations and tractions with associated boundary conditions, e.g. the Fleck and Hutchinson extension of the J_2 flow theory [2], were shown to capture relatively well many size effects observed experimentally [1-3]. In [2], a generalized effective plastic strain rate is defined, involving the magnitude of the plastic strain tensor and its gradient as well as intrinsic length parameters setting the scales at which plastic gradients play a role. The influence of strain gradients is incorporated in the plastic regime via the expression of the plastic work including higher order terms. This results in a set of two equations to solve – the equilibrium equation and a consistency equation – within a purely incremental framework.

In the implementation of such higher order phenomenological theories, the effective plastic strain field and the displacement field are considered as unknowns on equal footing. Higher order boundary conditions are therefore required at the external boundary of a region in which plastic flow occurs as well as at the internal boundary of the plastic region. These conditions usually do not vary at a given interface along the mechanical loading, and are motivated from the physical understanding of the dislocation mechanics at the interface between two phases. An interface between two different and strongly bonded phases is usually impenetrable to dislocations and is thus modelled by an essential boundary condition preventing any plastic deformation variation along the interface. On the contrary, if dislocations can pass through the surface unimpeded, a natural boundary condition with a vanishing higher order traction is applied. The choice of accurate boundary conditions at elasto-plastic boundaries is strongly debated in the literature and can lead to strong effects. A key feature however

is associated with the incremental nature of the formulation proposed in [2]. Indeed, the fact that the implementation uses effective plastic strain variations as primary unknowns eases the representation of an evolving plastic confinement at pre-defined interfaces in the microstructure.

In this contribution, two important problems will be investigated in which the incorporation of an *evolving* plastic confinement plays a major role and will be underlined.
First, the TRIP effect, which occurs with the partial transformation of a metastable residual austenitic phase into a harder martensitic phase under mechanical loading, will be addressed. Such a transformation is accompanied with a transformation strain, and leads to an extra contribution in hardening of the multiphase steel through two mechanisms [5]. The change of properties in a portion of the inclusion transforming into a much harder material contributes to the increase of the global strengthening through a classical composite effect. Secondly, the initially free interface between the inclusion and the transforming zone becomes impenetrable to dislocations. This evolving effect can be modelled phenomenologically with an evolving boundary condition on the plastic field, and induces an additional higher order effect caused by the presence of plastic strain gradients in the ferritic matrix surrounding the transforming zone. Using computational homogenisation concepts, a two-dimensional embedded cell model of an austenite inclusion containing the transforming region and surrounded by a ferritic matrix will be used. The results obtained with the strain gradient plasticity theory will be analysed, and compared to classical plasticity [6]. In particular, the significant influence of the intrinsic length on the compressive state in the transformed phase will be underlined.
As a second illustrative application, the effect of evolving plastic confinement at grain boundaries in a polycrystal will be investigated. An implementation incorporating an evolving essential plastic boundary condition at grain boundaries will be defined in order to represent the evolution of the grain boundary constraint from fully impenetrable at low dislocation density to partially transparent when a steady state recovery/dislocation multiplication process develops [7].

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