Abstract

Modelling highly non-linear, strongly temperature- and rate-dependent visco-plastic behaviour of poly-crystalline solids (e.g., metals and metallic alloys) is one of the most challenging topics of contemporary research interest, mainly owing to the increasing use of metallic structures in engineering applications. Numerous classical models have been developed to model the visco-plastic behaviour of poly-crystalline solids. However, limitations of classical visco-plasticity models have been realized mainly in two cases: in problems at the scale of mesoscopic length (typically in the range of a tenth of a micron to a few tens of micron) or lower, and in impact problems under high-strain loading with varying temperature. As a remedy of the first case, several length scale dependent non-local visco-plasticity models have been developed in the last few decades. Unfortunately, a rationally grounded continuum model with the capability of reproducing visco-plastic response in accord with the experimental observations under high strain-rates and varying temperatures remains elusive and attempts in this direction are often mired in controversies. With the understanding of metal visco-plasticity as a macroscopic manifestation of the underlying dislocation motion, there are attempts to develop phenomenological as well as physics-based continuum models that could be applied across different regimes of temperature and strain rate. Yet, none of these continuum visco-plasticity models accurately capture the experimentally observed oscillations in the stress-strain response of metals (e.g. molybdenum, tantalum etc.) under high strain rates and such phenomena are sometimes even dismissed as mere experimental artefacts. The question arises as to whether the existing models have consistently overlooked any important mechanism related to dislocation motion which could be very important at high strain-rate loading and possibly responsible for oscillations in the stress-strain response.

In the search for an answer to this question, one observes that the existing macro-scale continuum visco-plasticity models do not account for the effects of dislocation inertia which is identified in this thesis as a dominating factor in the visco-plastic response under high strain rates. Incorporating the effect of dislocation inertia in the continuum response, a visco-plasticity model is developed. Here the ow rule is derived based on an additional balance law, the micro-force balance, for the forces arising from (and maintaining) the plastic flow. The micro-force balance together with the classical momentum balance equations thus describes the visco-plastic response of isotropic poly-crystalline materials. The model is thermodynamically consistent as the constitutive relations for the fluxes are determined on satisfying the laws of thermodynamics. The model includes consistent derivation of temperature evolution, thus replaces the empirical route.

Partial differential equations (PDEs) describing the visco-plastic behaviour in the present model is highly non-linear and solving them requires the employment of numerical techniques. Had the interest been limited only to problems with nicely behaved continuous field variables, the finite element method (FEM) could have been a natural choice for solving the governing PDEs. Keeping in mind the limitations of the FEM in discretizing such large deformation problems and in handling discontinuities, a smooth particle hydrodynamics (SPH) formulation for the micro-inertia driven visco-plasticity model is undertaken in this thesis. The visco-plasticity model is then exploited to simulate ductile damage by suitably coupling the discretized SPH equations with an existing damage model. The current scheme does not necessitate the introduction of a yield or damage surface in evolving the plastic strain/ damage parameters and thus the numerical implementation avoids a computationally

intensive return mapping. Our current approach therefore provides for an efficient numerical route to simulating impact dynamics problems.

However, implementation of the SPH equations demands some additional terms such as artificial viscosity to arrive at a numerically stable solution. Using such stabilizing terms is however bereft of a rational or physical basis. The choice of artificial viscosity parameters is ad-hoc -an inappropriate choice leading to unphysical solutions. In order to circumvent this, the micro-inertia driven visco-plasticity model is reformulated using peri dynamics (PD), a more efficacious scheme to treat shock waves/discontinuities within a continuum model. Remarkably, the PD model naturally accounts for the localization residual terms in the local balances for internal energy and entropy, originally conceived of by Edelen and co-workers nearly half a century ago as a source of non-local interaction.

Exploiting the present model, we also explore the determination of conservation laws based on a variational formulation for dissipative visco-plastic solids wherein the system variables are appropriately augmented with those describing the time-reversed dynamics. This in turn enables us to undertake symmetry analyses on the resulting Lagrangian to assess, for instance, material resistance to crack propagation. Specifically, our results confirm that materials with higher rate sensitivity tend to offer higher resistance to fracture. Moreover, it is found that the kinetic energy of the inertial forces contributes to increased plastic flow thereby reducing the available free energy for crack propagation. This part of the work potentially opens a model-based route to the design of micro-defect structures for optimal fracture resistance.