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Microstructural constitutive model for polycrystal viscoplasticity in cold and warm regimes based on continuum dislocation dynamics

S. Amir H. Motaman*, Ulrich Prahl

Department of Ferrous Metallurgy, RWTH Aachen University, Intzestr. 1, Aachen D-52072, Germany

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ABSTRACT

Viscoplastic flow of polycrystalline metallic materials is the result of motion and interaction of dislocations, line defects of the crystalline structure. In the microstructural/physics-based constitutive model presented in this paper, the main underlying microstructural processes influencing viscoplastic deformation and mechanical properties of metals in cold and warm regimes are statistically described by the introduced sets of postulates/axioms for continuum dislocation dynamics (CDD). Three microstructural (internal) state variables (MSVs) are used for statistical quantifications of different types/species of dislocations by the notion of dislocation density. Considering the mobility property of dislocations, they are categorized to mobile and (relatively) immobile dislocations. Mobile dislocations carry the plastic strain (rate), while immobile dislocations contribute to plastic hardening. Moreover, with respect to their arrangement, dislocations are classified to cell and wall dislocations. Cell dislocations are those that exist inside cells/subgrains, and wall dislocations are packed in (and consequently formed) the subgrain walls/boundaries. Therefore, the MSVs incorporated in this model are cell mobile, cell immobile and wall immobile dislocation densities. The evolution of these internal variables is calculated by means of adequate equations that characterize the dislocation processes dominating material behavior during cold and warm monotonic viscoplastic deformation. The constitutive equations are then numerically integrated; and the constitutive parameters are determined/fitted for a widely used ferritic-pearlitic steel (20MnCr5).

1. Introduction

Nowadays, finite element (FE) simulation of manufacturing processes such as metal forming is an important part of process and product design and development in the industry. Correct and accurate description of material behavior and properties is always the biggest challenge in simulation of industrial manufacturing processes that are based on viscoplastic deformation. Dislocation-density-dependent physics-based constitutive models of metal plasticity while are computationally efficient and history-dependent, can accurately account for varying process parameters such as strain rate and temperature. Since these models are founded on essential phenomena dominating the deformation, they have a wide range of usability and validity. Moreover, they are suitable for manufacturing chain simulations as they can efficiently compute the cumulative

* Corresponding author.
E-mail address: seyedamirhossein.motaman@iehk.rwth-aachen.de (S. Amir H. Motaman).

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Nomenclature

Symbol description

b	Burgers length (magnitude of Burgers vector)	[m]
c	Material coefficient associated with probability amplitude (or frequency) of a dislocation process	[-]
d	Critical distance for dislocation processes	[m]
e	Relative error, residual/objective/fitness function	[%]
f	Volume fraction	[-]
G	Shear modulus	[Pa]
H	Viscoplastic tangent modulus	[Pa]
l	Length of a dislocation segment	[m]
m	Strain rate sensitivity parameter	[-]
n	Number of active slip/glide systems	[-]
M	Taylor factor	[-]
p	Probability amplitude (or frequency) of a dynamic dislocation process	[-]
q	Volumetric heat generation	$[\mathrm{J{\cdot}m^{-3}}]$
r	Temperature sensitivity coefficient	[-]
R	Dislocation radius	[m]
s	Temperature sensitivity exponent	[-]
$\boldsymbol{S}$	Stochastic/nonlocal microstructural state	[a set containing all MSVs]
t	Time	[s]
T	Temperature	[K]
u	Volumetric stored energy	$[\mathrm{J{\cdot}m^{-3}}]$
v	Velocity vector	$[\mathrm{m{\cdot}s^{-1}}]$
w	Volumetric work	$[\mathrm{J{\cdot}m^{-3}}]$
α	Dislocation interaction strength/coefficient	[-]
β	Dissipation factor, efficiency of plastic dissipation, or Taylor–Quinney coefficient	[-]
γ	Shear strain in slip system, mean shear strain	[-]
ε	Mean/nonlocal true (normal) strain	[-]
θ	Plastic/strain hardening	[Pa]
φ	Viscous/strain-rate hardening	[Pa.s]
κ	Material constant associated with dissipation factor	[-]
Λ	Dislocation spacing	[m]
ρ	Dislocation density	$[\mathrm{m^{-2}}]$
σ	Mean/nonlocal true (normal) stress	[Pa]
τ	Resolved shear stress	[Pa]

Index description

ac	Accumulation
an	Annihilation
d	Dynamic
gn	Generation
GN	Geometrically necessary
i	Immobile
loc	Local
m	Mobile, melt
(n)	Time step index, previous time increment
$(n+1)$	Current time increment
nc	Nucleation
c	Cell
p	Plastic
pn	Pinning
rm	Remobilization
s	Static
sat	Saturated
SS	Statistically stored
t	Total (subscript), time (superscript)
tr	Trapping
$\boldsymbol{v}$	Viscous