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Modeling the viscoplastic flow behavior of a 20MnCr5 steel grade deformed under hot-working conditions, employing a meshless technique

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A B S T R A C T

The present work has been conducted in order to develop a novel approach to predict the inhomogeneous flow of a 20MnCr5 steel during an axisymmetric hot compression test, by using the element-free Galerkin (EFG) method under a differential constitutive description. The governing equations have been solved on the basis of the EFG global weak formulation. A detailed explanation concerning the characteristics inherent to the application of the EFG method to this problem, has also been provided. Furthermore, a return mapping algorithm for the solution of associative von Mises inelastic problems, has been formulated for the differential constitutive description employed in this communication, namely, a differential return mapping algorithm (DRMA). The feasibility and suitability of the EFG method for solving the axial compression problem has been shown by comparing its results with a FEM based solution employing a simple constitutive description. The reliability of the proposed DRMA has been demonstrated by a comparison of a homogeneous deformation numerical test with the experimental and direct integration results reported in a previous communication. Finally, the EFG model has been used to predict the stress, strain and volume fraction recrystallized distributions under steady and transient nominal strain rate and temperature deformation conditions. These parametric studies have been carried out by considering the differential constitutive description, but also a conventional integrated constitutive model of a 20MnCr5 steel. The results have revealed the suitability of the EFG formulation under the proposed DRMA, for predicting the performance of an axisymmetric hot compression test. The differences between the use of differential and integrated constitutive descriptions on the performance of hot-working processes under inhomogeneous deformation conditions, have also been evidenced in this research work.

1. Introduction

The prediction of the inelastic flow and stress distributions during industrial hot-working processes is a matter of great interest. During these metal-forming processes, the viscoplastic flow of structural steels involves several microstructural phenonema, which govern the material constitutive behavior. The work-hardening (WH), dynamic recovery (DRV) and dynamic recrystallization (DRX) processes are the main controlling mechanisms of the steel mechanical behavior during the viscoplastic flow. The aforementioned microstructural processes are mainly governed by the strain rate and deformation temperature, which undergo significant changes

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Nomenclature

Linear momentum balance

σ_{ij} Stress tensor (MPa)
F_i Field forces (N/mm^3)
$d\varepsilon_{ij}$ Incremental strain tensor
$d\varepsilon_{ij}^{vp}$ Incremental viscoplastic strain tensor
σ'_{ij} Deviatoric stress tensor (MPa)
$\overline{\sigma}^{vm}$ Von Mises effective stress (MPa)
σ_y Yield stress (MPa)
$d\lambda$ Plastic multiplier

EFG formulation for the linear momentum balance

$K^{2n\times 2n}$, $K_{ij}^{2\times 2}$ Stiffness matrix/binodal assembling components
$P^{2n\times 2n}$, $P_{ij}^{2\times 2}$ Penalty matrix/binodal assembling components
Q_t^{2n}, $Q_i^{(t)2\times 1}$ Surface loads vector/nodal assembling components
Q_F^{2n}, $Q_i^{(F)2\times 1}$ Field loads vector/nodal assembling components
Q_σ^{2n}, $Q_i^{(\sigma)2\times 1}$ Internal loads vector/nodal assembling components
Q_{vp}^{2n}, $Q_i^{(vp)2\times 1}$ Viscoplastic flow loads vector/nodal assembling components
Q_P^{2n}, $Q_i^{(P)2\times 1}$ Penalty loads vector/nodal assembling components
dU^{2n}, $dU_j^{2\times 1}$ Nodal parameters incremental vector/nodal components

Voigt Notation for the axysimmetric problem

Strain Differential Operator: $[L^{4\times 2}]^T = \begin{bmatrix} \partial/\partial r & 1/r & 0 & \partial/\partial z \\ 0 & 0 & \partial/\partial z & \partial/\partial r \end{bmatrix}$

Fourth Order Symmetric Tensor: $I_S^{4\times 4} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1/2 \end{bmatrix}$

Kronecker Delta Tensor: $[\overline{\overline{\delta}}^{4\times 1}]^T = [1 \ \ 1 \ \ 1 \ \ 0]$

Stress Tensor: $[\overline{\overline{\sigma}}^{4\times 1}]^T = [\sigma_{rr} \ \ \sigma_{\theta\theta} \ \ \sigma_{zz} \ \ \sigma_{rz}]$

Deviatoric Stress Tensor: $\overline{\overline{\sigma}}'^{4\times 1} = \overline{\overline{\sigma}}^{4\times 1} - \overline{\overline{\delta}}^{4\times 1}(\sigma_{rr} + \sigma_{\theta\theta} + \sigma_{zz})/3$

Incremental strain tensor: $[d\overline{\overline{\varepsilon}}^{4\times 1}]^T = [du_r \ \ du_z][L^{4x2}]^T = [d\varepsilon_{rr} \ \ d\varepsilon_{\theta\theta} \ \ d\varepsilon_{zz} \ \ 2d\varepsilon_{rz}]$

Incremental inelastic (viscoplastic) strain Tensor: $d\overline{\overline{\varepsilon}}_{vp}^{4\times 1} = 3d\lambda \frac{\overline{\overline{\sigma}}'^{4\times 1}}{\overline{\sigma}^{vm}} \begin{bmatrix} 1/2 & 0 & 0 & 0 \\ 0 & 1/2 & 0 & 0 \\ 0 & 0 & 1/2 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

under real industrial manufacturing conditions. Real industrial hot-working processes imply significant changes in temperature and strain rate during the inelastic deformation. Even during a geometrically simple deformation process such as an axisymmetric compression test, it is not possible to achieve a constant strain rate under realistic conditions as a consequence of the friction at the platen/workpiece interface. The frictional forces give rise to an inhomogeneous deformation condition, which results in permanent strain rate variations of each material point during the entire deformation process. This condition cannot be circumvented even by imposing a constant nominal effective strain rate, which is defined as the ratio of the crosshead speed to the instantaneous height of the specimen. Recently, several researchers have employed the FEM in order to predict the displacement, stress and strain distributions during large-strain and path-dependent processes under both, hot and cold-working conditions(Zeng et al., 2011; Goodarzi Hosseinabadi and Serajzadeh, 2013; Hossein-Zadeh et al., 2012; Camacho et al., 2014; Hong, 2015). Zeng et al. (2011) determined the friction factor of Ti-6Al-4V titanium alloy under hot-forging and non-isothermal conditions, by combining hot-ring compression tests with FEM simulations. The FEM simulations presented an excellent agreement with the experimental results. Goodarzi Hosseinabadi and Serajzadeh (2013) have carried out a thermal-mechanical analysis of a cold extrusion process using the FEM under a stream-function formulation. In this approach, the geometry of the deformation zone is predicted based on a prescribed velocity field, which is useful to avoid re-meshing procedures between successive material configurations. Hossein-Zadeh et al. (2012) have determined the strain field in a tube radial forging process through a numerical-experimental technique, which involves FEM simulations and micro-hardness tests. In this work a hardness-strain relationship computed by the experimental measurements and FEM simulation results of an axial compression test, has been coupled with the micro-hardness data of a radial forging process to predict the related strain distribution, which has been compared with a FEM analysis of the same process. Regarding the axisymmetric compression processes, Camacho et al. (2014) have carried out a study about the pressure contact profiles over the platens/workpiece interface, based on a FEM analysis. The outcomes of this work have proven that the contact pressure profiles exhibit significant dependence on the ratio of height to cylinder diameter H/D. The results have depicted that for H/D values greater than 0.5, the contact pressure profiles exhibit a behavior practically opposite to the conventional *friction hills*, which are obtained under the simplifications of the slab method analytical approach. The FEM has also been employed to carry out inverse analysis in order to predict the friction conditions during axisymmetric cold compression tests(Hong, 2015). The FEM models mentioned so far are based on standard conventional constitutive models, which are available in the materials libraries of widely employed commercial software (ANSYS, FORGE, ABAQUS and DEFORM 2D-3D). Among such constitutive relationships, the most widely employed in numerical simulations are: perfect plastic, linear-hardening, Hollomon, Modified Hollomon, Ludwig, Modified Ludwig and Hansel-Spittel models. These constitutive models have been successfully used to describe the materials mechanical behavior in several metal-forming processes, especially under semi-solid state and cold-working conditions(Goodarzi Hosseinabadi and Serajzadeh, 2013; Hossein-Zadeh et al., 2012; Camacho et al., 2014; Hong, 2015; Shashikanth and Davidson, 2014; Alankar and Wells, 2010). However, these constitutive models are not suitable when the material viscoplastic flow under hot-working conditions involves several controlling mechanisms such as WH, DRV and DRX. For instance, steel hot-forming processes involve the aforementioned controlling mechanisms under austenization conditions. Therefore, several researchers have recently carried out thermal-mechanical analysis