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Analysis of metal extrusion by the Finite Volume Method

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Abstract

Present work examines and validates the novel numerical scheme to calculate the velocity, stress, strain, pressure and strain rate fields of metal plastic flow in direct extrusion processes by employing the finite volume method, FVM. Traditionally, the classical methods such as the upper-bound, slab, slip-line and more recently the Finite Element Method have been largely applied in metal extrusion analysis. However, recently the FVM has been applied and published by the authors for analysis of metal plastic flow, concluding that direct extrusion of metals could be mathematically modelled by the plastic flow formulation similar to an incompressible non-linear viscous fluid. Tannehill et al. suggested that viscous fluid flow can be numerically simulated by FVM, obeying the mass, momentum and energy conservation equations and boundary conditions. Hence, the governing equations of metal plastic flow in Euler approach were discretized by FVM, using the Explicit MacCormack Method in structured, fixed and collocated mesh. SIMPLE method was applied to attain the necessary pressure-velocity coupling. These new numerical scheme was applied to the analysis of direct hot extrusion process of Al 6351 and Al 6060 aluminium alloys. The velocity and other variables fields achieved fast convergence and a good agreement with experimental results from visioplasticity tests by the grid stripe pattern technique and Forge 2008 software. The MacCormack Method applied to metal extrusion revealed consistent results without the need of artificial viscosity as required by the compressible fluid flow simulation approaches. Therefore, present numerical results confirm that FVM with MacCormack method together with Euler formulation approach and SIMPLE method can be applied satisfactory in the solution of metal forming processes.

Keywords: metal extrusion; FVM; stripe technique; aluminum alloy; lead.

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1. Introduction

Generally, extrusion of metals is a thermo-mechanical processing at warm and high temperature by which metallic alloys billets are transformed into simple bar, rod, profiles or bars of complex cross sectional shape. The successful operation, direct or back extrusion, involves the knowledge of the mechanics of metal flow (velocity, pressure, stresses and deformations fields), heat transfer, friction and the metallurgy of microstructure evolution (grain size, phase, porosity, damage, etc.), to manufacture the required quality of product physical and mechanical properties. Nowadays, both analyses are increasingly performed by numerical simulation with the aid of computers and software. Thus, modelling the mechanics of metal flow and microstructure evolution in metal forming is a modern and intense topic of scientific research in industry and academy.

Nomenclature

r, θ, z	radial, angular and axial coordinates in cylindrical coordinate system (r,θ,z) respectively
v_r, v_z	velocity vector components
σ_{rr}, $\sigma_{\theta\theta}$, σ_{zz}	normal components of Cauchy stress tensor $\boldsymbol{\sigma}$
σ_{rz}	shear stress component of Cauchy stress tensor $\boldsymbol{\sigma}$
σ_m	hydrostatic pressure, $\sigma_m = (\sigma_{rr} + \sigma_{\theta\theta} + \sigma_{zz}) / 3$
s_{ij}	deviatoric stress, $s_{ij} = \sigma_{ij} - \sigma_m \delta_{ij}$
ε, $\dot{\varepsilon}$	true strain, strain rate tensor
ρ, c, T	density, specific heat and temperature respectively
$\dot{q}_r$, $\dot{q}_z$	components of heat flow vector $\dot{\boldsymbol{q}}$
$\bar{\sigma}$	effective or equivalent stress, $\bar{\sigma} = \sqrt{(3/2) s_{ij} s_{ij}}$
$\dot{\lambda}$	plasticity multiplier, $\dot{\lambda} = 3\dot{\bar{\varepsilon}} / 2\bar{\sigma}$
η	metal equivalent viscosity
$\dot{\bar{\varepsilon}}$	effective or equivalent plastic strain rate, $\dot{\bar{\varepsilon}} = \sqrt{(2/3)\dot{\varepsilon}_{ij}\dot{\varepsilon}_{ij}}$
m	friction factor , $\tau_{nt} = mk$, where τ_{nt} is the tangential friction stress
$t, \Delta t$	time, virtual time step respectively
$\boldsymbol{Q}$, $\boldsymbol{F}_r$, $\boldsymbol{F}_z$ and $\boldsymbol{S}$	flow vectors
V_{mn}	control volume of node *mn*
$\underline{Q}_{mn}^{t+1}$, $\underline{\underline{Q}}_{mn}^{t+1}$, Q_{mn}^{t+1}	predictor step, corrector step and current step respectively
A, m_1, m_2, m_3, m_4, m_5, m_6, m_7, m_8	material parameters of Hansel-Spittel equation

Traditionally, the classical methods such as the slab, slip-line, upper-bound [1,2] and more recently the Finite Element Method have been largely applied in metal extrusion modelling and analysis. In addition, the experimental technique of visioplasticity methods employed to analyses metal flow and validate the theoretical models have been the bi-sectioned billet with scratched grid pattern, stripe pattern grid and colour plasticine. Lead and aluminium have also been employed extensively at room temperature to obtain and analyse the metal flow fields. Materials which are commonly extruded by industries are copper, brass, aluminium, steel, titanium and magnesium alloys.

The aim of present work is to employ the FVM to a novel numerical scheme to analyse the mechanics of metal flow in direct extrusion of aluminium alloys in 32.3° and 13.4° semi-die angles and compare them with experimental results from bi-sectioned billet with stripe pattern grid technique and Forge software. A secondary aim is to develop a unified approach that could be used in conjunction with microstructure evolution models, based on physical metallurgy laws, to predict the physical and mechanical properties of the final extrusion product.

2. Mathematical modelling of metal extrusion by the Finite Volume Method

The analysis of the mechanics of metal flow and microstructure evolution can be treated as separated issues [3]. Recently, a novel numerical scheme has been developed and applied successfully by the authors [4] for analysis of metal plastic flow, concluding that direct extrusion of metals could be mathematically modelled by the plastic flow