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Thermomechanical modeling and simulation of aluminum alloy behavior during extrusion and cooling

*F. Parvizian**, *T. Kayser, C. Hortig, B. Svendsen*

University of Dortmund, Chair of Mechanics, 44227 Dortmund, Germany

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ABSTRACT

The purpose of this work is the modeling and simulation of aluminum alloys during extrusion processes. In particular, attention is focused here on aluminum alloys of the 6000 series (Al—Mg— Si) and 7000 series (Al— Zn— Mg). In the current paper, a number of aspects of the structural simulation as well as that of extrusion as a thermomechanical process are considered. These aspects include contact and adaptive mesh refinement, heat transfer inside the billet, heat transfer between the workpiece and the container, frictional dissipation, mechanical energy and surface radiation. The friction is considered to model the so called "dead material zone". The radiation constant has been estimated so that the results are close to the experimental results.

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1. Introduction

Extrusion as a technological process is used to produce profiles with constant cross sections from materials such as aluminum, copper, stainless steel and various types of plastic. The advantages of aluminum and its alloys include high ductility (due to its fcc crystal structure), making it particularly suitable for complex extrusion processes. Additionally, the ideal ratio of Young's modulus to mass density in aluminum makes it ideal for a wide range of application in automotive and aircraft manufacturing, as well as for lightweight construction in general. The process of extrusion in combination with heat treatment and further processing, e.g., bending, leads to a complex microstructure development in the material. An understanding of this development in each processing step especially during extrusion and heat treatment allows one to influence and control the resulting material properties.

Simulation of hot forming processes with application of finite element method (FEM) has been the subject of many recent works. Large plastic deformations and high temperature of the extrusion process cause developments in the microstructure of the material. Shercliff and Lovatt (1999) have presented various physical and statistical approaches for modeling of microstructure evolution in hot deformation. In physically based state variable models, the microstructure and property evolution are modeled explicitly. In statistical approach the process conditions are linked empirically to the final microstructure. Furu et al. (1996) have offered a physically based model to describe the development of microstructure during hot forming processes which is later developed by Sellars and Zhu (2000) by applying the concept of free energy as the driving force of microstructure evolutions. Microstructure developments are temperature dependent processes, therefore for modeling these developments it is required to consider a coupled thermomechanical model. Several constitutive laws

* Corresponding author.
E-mail address: f.parvizian@mech.mb.uni-dortmund.de (F. Parvizian).
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have been used by different research groups. Duan et al. (2004) have investigated the influence of the constitutive equation on the simulation of a hot rolling process. Duan and Sheppard (2003) have applied the isotropic viscoplastic Norton–Hoff law as the flow rule. Nes (1995) has used the hyperbolic sine law as the governing constitutive equation which is a purely empirical model suggested for metal forming processes such as hot rolling, forging and extrusion. This model is also employed by Sheppard (2006) for prediction of structure during extrusion process and also by Zhang et al. (2007) for material behavior of some new aluminum alloys in hot forming processes. In another work Bontcheva et al. (2006) have applied the "Shvarzbart" model for large deformations to describe the thermomechanical behavior of the material.

In the current work, attention is focused on certain aspects of the numerical simulation of extrusion and cooling including (1) contact and friction conditions, (2) adaptive mesh refinement, (3) thermomechanical behavior of material during extrusion and (4) conductive, convective and surface radiation cooling. The current approach is based on a continuum thermodynamic model formulation for thermoelastic, thermoviscoplastic material behavior of metallic materials. Rather than on the more realistic model of Sellars and Zhu (2000), the current material model assumes for simplicity a Johnson–Cook-like approach for the evolution of the accumulated equivalent inelastic deformation as a function of the stress, accumulated inelastic deformation and temperature.

2. Material model

Although not the principle focus of the current work, we outline the formulation of the material model used in this work in this section for completeness. The same general approach sketched below is also that used for much more detailed material modeling in work in progress building on that of Sellars and Zhu (2000).

The current approach is based on a large-deformation thermoelastic, thermoviscoplastic description of aluminum alloys at high temperature. In this context, local inelastic deformation is represented by a deformation-like quantity $\mathbf{F}_\mathrm{P}$. This induces the part

$$\mathbf{F}_\mathrm{E} = \mathbf{F}\mathbf{F}_\mathrm{P}^{-1} \tag{1}$$

of the deformation gradient $\mathbf{F}$ interpreted as being elastic in this context and a measure of energy storage in the material. The free energy density depends on the temperature θ, local elastic deformation $\mathbf{F}_\mathrm{E}$ and internal state variables $\epsilon_1, \ldots$

$$\psi = \psi(\theta, \mathbf{F}_\mathrm{E}, \epsilon_1, \ldots). \tag{2}$$

This in turn determines the Kirchhoff stress

$$\mathbf{K} = \mathbf{P}\mathbf{F}^\mathrm{T} = (\partial_{\mathbf{F}_\mathrm{E}}\psi)\mathbf{F}_\mathrm{E}^\mathrm{T} \tag{3}$$

and the flow rule

$$\dot{\mathbf{F}}_\mathrm{P} = \dot{\alpha}_\mathrm{P}\mathbf{N}_\mathrm{Pi}\mathbf{F}_\mathrm{P}. \tag{4}$$

Here, α_P is the accumulated inelastic deformation and $\mathbf{N}_\mathrm{Pi}$ is the flow direction. The evolution of internal variables $\epsilon_1, \ldots$ takes an analogous form

$$\dot{\epsilon}_\mathrm{i} = \dot{\alpha}_\mathrm{P}\pi_\mathrm{i} \tag{5}$$

depending on α_P. In more advanced models such as Sellars and Zhu (2000), $\epsilon_1, \ldots$ represent such quantities as the subgrain size, grain misorientation and dislocation density.

Next, attention is restricted to isotropic material behavior. In addition, the simplifying assumption of constant heat capacity is made here. Assuming then that the free energy density can be split into a sum of elastic and inelastic parts, one obtains

$$\psi = \psi_\mathrm{E}(\theta, \ln \mathbf{V}_\mathrm{E}) + \psi_\mathrm{P}(\theta, \epsilon_1, \ldots), \tag{6}$$

where $\ln \mathbf{V}_\mathrm{E}$ is the elastic left logarithmic stretch tensor following from the polar decomposition of $\mathbf{F}_\mathrm{E} = \mathbf{V}_\mathrm{E}\mathbf{R}_\mathrm{E} = \mathbf{R}_\mathrm{E}\mathbf{U}_\mathrm{E}$. Here,

$$\psi_\mathrm{E}(\theta, \ln \mathbf{V}_\mathrm{E}) = \varepsilon_\mathrm{E0}(\ln \mathbf{V}_\mathrm{E}) - \theta\,\eta_\mathrm{E0}(\ln \mathbf{V}_\mathrm{E}) + \rho c_0\{\theta - \theta_0 - \theta\,\ln(\theta/\theta_0)\} \tag{7}$$

represents the elastic part of this energy, ρ is the density of the material and c_0 is the specific heat capacity of the material. The elastic part of energy consists of internal energetic

$$\varepsilon_\mathrm{E0}(\ln \mathbf{V}_\mathrm{E}) = \kappa_0\,\mathrm{tr}(\ln \mathbf{V}_\mathrm{E})^2/2 + 3\kappa_0\alpha_0\theta_0\,\mathrm{tr}(\ln \mathbf{V}_\mathrm{E}) + \mu_0\,|\mathrm{dev}(\ln \mathbf{V}_\mathrm{E})|^2 \tag{8}$$

and configurational entropic

$$\eta_\mathrm{E0}(\ln \mathbf{V}_\mathrm{E}) = 3\kappa_0\alpha_0\,\mathbf{I}\ln \mathbf{V}_\mathrm{E} \tag{9}$$

parts. Here κ_0 is the bulk modulus of the material and μ_0 and α_0 represent the shear modulus and thermal expansion coefficient of the material, respectively. Likewise, the inelastic free energy density is given by

$$\psi_\mathrm{P} = \varepsilon_\mathrm{P0}(\epsilon_1, \ldots) - \theta\,\eta_\mathrm{P0}(\epsilon_1, \ldots) \tag{10}$$

as a linear function of the temperature θ and internal state variables $\epsilon_\mathrm{i}, \ldots$. From (7), the isotropic Kirchhoff stress takes the form

$$\mathbf{K} = \partial_{\ln \mathbf{V}_\mathrm{E}}\,\psi_\mathrm{E} = \kappa_0\,\{\mathrm{tr}(\ln \mathbf{V}_\mathrm{E}) - 3\,\alpha_0(\theta - \theta_0)\}\mathbf{I} + 2\mu_0\,\mathrm{dev}(\ln \mathbf{V}_\mathrm{E}). \tag{11}$$

On the basis of assuming Fourier heat conduction

$$\mathbf{q} = -k_0\nabla\theta, \tag{12}$$

temperature changes due to elastic and inelastic heating can be found from

$$\rho c_0\,\dot{\theta} = -3\,\kappa_0\,\alpha_0\,\theta\,\dot{\overline{\ln(\det(\mathbf{F}))}} + \beta\,\sigma\,\dot{\alpha}_\mathrm{P} + k_0\nabla^2\theta, \tag{13}$$

where k_0 is the material conductivity and σ the effective stress given by the von Mises stress

$$\sigma = \sqrt{\frac{3}{2}}|\mathrm{dev}(\mathbf{K})|. \tag{14}$$

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