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Technical Paper

Steady-state numerical modeling of size effects in micron scale wire drawing

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ABSTRACT

Wire drawing processes at the micron scale have received increased interest as micro wires are increasingly required in electrical components. It is well-established that size effects due to large strain gradient effects play an important role at this scale and the present study aims to quantify these effects for the wire drawing process. Focus will be on investigating the impact of size effects on the most favourable tool geometry (in terms of minimizing the drawing force) for various conditions between the wire/tool interface. The numerical analysis is based on a steady-state framework that enables convergence without dealing with the transient regime, but still fully accounts for the history dependence as-well as the elastic unloading. Thus, it forms the basis for a comprehensive parameter study. During the deformation process in wire drawing, large plastic strain gradients evolve in the contact region. This creates a need for a higher order plasticity theory to accurately predict the material behaviour across the multiple scales involved. The present study reveals that the contribution from an energetic (recoverable) length parameter is limited, while the corresponding dissipative contribution dominates and tends to shift the drawing force to a higher level. As a direct consequence, the strain gradient hardening effect reduces the most favourable tool angle of a sharp tool with up to 50% (in terms of the required drawing force), whereas a circular shaped tool is proven less sensitive to scaling effects. By considering the contact force profile between tool and material it becomes clear that the strain gradients have a smoothing effect and both the magnitude and position of the peak pressure are affected significantly. A round tool is found to reduce the peak force, while the location of the peak is found to move from outlet to inlet depending on the tool geometry.

1. Introduction

The wire drawing process is used in manufacturing at all scales, ranging from several centimetres to a few microns. The growing production of micro components has increased the demand for micro wires (<10 μm), which is an important component in e.g. semiconductors and electrical winding coils. At this scale, size effects are highly important in the production and therefore requires attention. It is well established that the size effect, appearing as either increased hardening or strengthening at the micron scale, originates from large strain gradients created by the inhomogeneous deformation during the wire drawing process.

Size effects can originate from two different sources, namely the effect of geometrically necessary dislocations (GNDs) which follows from the development of large plastic strain gradients and the effect of the microstructure when the grains become comparable in size to the wire diameter. The present study, however, investigates only the size effect related to the GNDs, while assuming homogeneity of the material, thus disregarding grain size effects. Storage of GNDs [1,6,15] gives rise to free energy (energetic contribution) associated with the local stress field of the GNDs (dislocation pile-ups) and an increased dissipation (dissipative contribution) when the GNDs move through the lattice. The dissipative and energetic part are commonly referred to as length parameters in higher order plasticity theories. The length parameter ensures dimensional consistency in the model and essentially allows for a change in material behaviour across scales (see Mu et al. [8] for a recent attempt to relate the length parameter to experimental findings at the micron scale). At the micron scale, GNDs can dominate the total dislocation density, which is normally dominated by statistically stored dislocations (SSDs) at larger scales. This leads to a requirement for additional energy to deform the material in the presence of large plastic strain gradients. This effect will create an apparent increase in yield stress as-well as additional hardening of the material.

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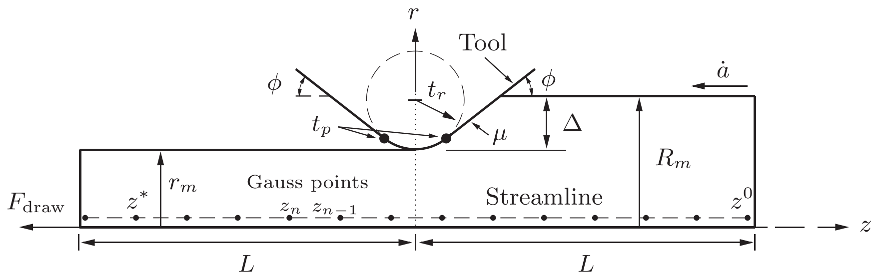

Fig. 1. Parametrization of the wire drawing process in the adopted steady-state framework with axisymmetry around the z-axis. Throughout the study, $R_m/(2L) = 1/10$ and the finite element mesh employed consists of square elements with side length $L^{(e)}/R_m = 20$.

To accommodate these issues, and develop a numerical model capable of handling this complex behaviour, the material model must represent the field quantities over the full range of length scales involved. In the present study, the higher order elastic–viscoplastic theory suggested by Fleck and Willis [4] is employed. Here, the concept of higher order stresses, work-conjugate to the strain gradients, is adopted to increase the size range for which the material model is valid.

Neglecting grain and microstructure effects, the wire drawing process is a continuous process, making it ideal for a steady-state framework. Thus, the transient regime in the initial phase of the wire drawing process is not analysed in the present study. Avoiding the transient regime presents a number of advantages such as not having to deal with a continuously changing contact region (see e.g. Richelsen [17] for a discussion related to a transient study of rolling). A numerical investigation of steady-state wire drawing at the micron scale can be found in Byon et al. [2]. Their work, however, is based on rigid plasticity where residual stresses and elastic unloading are neglected. At elevated temperatures (hot working), the effect of elastic unloading is minor, but at low temperatures (cold working), elastic unloading is essential. The steady-state model employed in the current study readily accounts for elastic unloading as-well as residual stresses, and it is based on the early work of Dean and Hutchinson [3] for continuous crack growth (see also Wei and Hutchinson [18]).

The developed model will be exploited to quantify the effect of strain gradients related to the most favourable tool geometry. During these studies both the effect of the dissipative and energetic length parameters are investigated (see e.g. Nielsen [9] and Nielsen et al. [13] for similar studies on steady-state rolling).

In the following sections, the basis for the model will be presented in tensor notation. The model is formulated in 2D, under the assumptions of axisymmetry, and thus the tensor notation should be interpreted as components 1, 2, 3 being the radial (r), axial (z), and angular (θ) direction, respectively. The notation $\dot{()}$ is used for the time derivative of a quantity. This paper is divided into the following sections: the parametrization of the wire drawing process is presented in Section 2, the material model and the numerical formulation are presented in Section 3, the boundary value problem is presented in Section 4, results are presented in Section 5 and lastly concluding remarks are given in Section 6.

2. Parametrization of the wire drawing process

The diameter of the undeformed wire is $2R_m$ and the reduced diameter after passing the tool is $2r_m$ (see Fig. 1). The tool consists of two linear parts (tool flanks) and a circular part (tool nose) of radius t_r. The linear and circular part of the tool is connected in the transition point, t_p, which is the point where the flank is tangent to the circle. For an increasing tool nose radius, t_r, the transitions points will move up, and ultimately they may coincide with the surface of the wire making the tool circular. The tool, as-well as the entire model, is revolved around the z-axis according to the axisymmetric formulation. Due to the axisymmetry, displacement constraints are not required along the z-axis, however, symmetry conditions are enforced on the plastic strains such that $\dot{\varepsilon}^p_{12} = 0$ at $r = 0$. The tool is assumed to be rigid and the maximum reduction of the wire radius, Δ, is located at the centre of the tool ($z = 0$). The final radius of the wire, r_m, will then correspond to the initial radius, R_m, minus the reduction, plus an elastic spring back. The quantities, besides material parameters found in Table 1, which are prescribed in the model is the radial reduction ratio, Δ/R_m, the normalized tool nose radius, t_r/R_m, the tool angle, ϕ (also called the semi-cone angle), and the dimensionless inlet velocity, $\alpha = \dot{a}/(\dot{\varepsilon}_0 R_m)$, with $\dot{\varepsilon}_0$ being the material reference strain rate and $\dot{a}$ being the actual inlet velocity ($\alpha = 50$ throughout the study). The influence of the velocity is depending on the magnitude of the rate hardening of the material (exponent, m, in Eq. (5)) and its influence can be significant.

Table 1
Mechanical properties.

Parameter	Significance	Value
σ_y/E	Yield strain	0.001
ν	Poisson's ratio	0.3
N	Strain hardening exponent	0.2
m	Strain rate hardening exponent	0.02
$\dot{\varepsilon}_0$	Reference strain rate	0.001
L_D	Dissipative length parameter	0.05–0.5R_m
L_E	Energetic length parameter	0–0.1R_m

3. Numerical framework

The numerical framework builds on the gradient enhanced elastic–viscoplastic theory proposed by Gudmundson [5]; Gurtin and Anand [7]; Fleck and Willis [4]. Here, the analysis is restricted to small strains as a first approximation by limiting the wire reduction to a maximum of 4% (the overall straining in the wire drawing process is proportional to the wire reduction for small reductions). The total strain, ε_{ij}, is determined from the displacements, such that $\varepsilon_{ij} = (u_{i,j} + u_{j,i})/2$ which can be decomposed into an elastic part, ε^e_{ij}, and a plastic part ε^p_{ij} ($\varepsilon_{ij} = \varepsilon^e_{ij} + \varepsilon^p_{ij}$). The displacement and plastic strain components obey the principle of virtual work (PVW) presented in Eq. (1) (given in Cartesian components), and they are determined from the *Minimum Principles I and II* presented by Fleck and Willis [4] (see also Section 3.1).

$$\int_V \left(\sigma_{ij}\delta\varepsilon_{ij} + (q_{ij} - s_{ij})\delta\varepsilon^p_{ij} + \tau_{ijk}\delta\varepsilon^p_{ij,k} \right) \mathrm{d}V = \int_S \left(T_i\delta u_i + M_{ij}\delta\varepsilon^p_{ij} \right) \mathrm{d}S \quad (1)$$

Here, q_{ij} is the micro-stress, σ_{ij} is the Cauchy stress, s_{ij} is the deviatoric stress, and τ_{ijk} is the higher order stress. The right-hand side of the PVW in Eq. (1) is divided into the conventional tractions $T_i = \sigma_{ij}n_j$ and the higher order tractions, $M_{ij} = \tau_{ijk}n_k$, where n_k