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Rolling induced size effects in elastic–viscoplastic sheet metals

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ABSTRACT

Rolling processes for which the characteristic length scale reaches into the range where size effects become important are receiving increased interest. In particulary, this is owed to the roll-molding process under development for high-throughput of micron-scale surface features. The study presented revolves around the rolling induced effect of visco-plasticity (ranging hot and cold rolling) in combination with strain gradient hardening – including both dissipative and energetic contributions. To bring out first order effects on rolling at small scale, the modeling efforts are limited to flat sheet rolling, where a non-homogeneous material deformation takes place between the rollers. Large strain gradients develop where the rollers first come in contact with the sheet, and a higher order plasticity model is employed to illustrate their influence at small scales. The study reveals that the energetic length parameter has negligible effect on the rolling quantities of interest, while the contribution coming from the dissipative length parameter can be dominant. Considering a slow and a fast moving sheet, respectively, convergence towards the rate independent limit is demonstrated, and a characteristic velocity is identified, for which the torque and punch force applied to the roller becomes independent of the material rate-sensitivity.

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1. Introduction

Rolling at small scale has recently received attention due to an apparent size effects observed when down-scaling experiments. One suspect to this is strain gradient hardening. It is well-established that with large plastic strain gradients come an increased hardening at micron scale – and rolling is no exception. As the sheet is forced between the rollers, a fairly heterogeneous evolution of plastic straining takes place and severe gradients develop (Richelsen, 1993, 1996). To accommodate the large plastic gradients, Geometrically Necessary Dislocations (GNDs) are forced to develop, and with the movement and storage of these additional dislocations come added free energy and dissipation (Ashby, 1970; Gurtin, 2002; Ohno and Okumara, 2007). At micron scale, GNDs can become a substantial portion of the total dislocation density, and thus dominate the amount of energy required to deform the material.

Nielsen et al. (2015) recently demonstrated rolling related size effects in the rate-independent limit of an elastic-viscoplastic solid (cold rolling), employing a steady-state numerical framework. By accounting for a dissipative length scale, it has been shown that the forces (punch force, roll torque, power input etc.), and hence the contact interface conditions, between the rollers and the sheet, generally displays increased levels. As discussed by Richelsen (1991), modeling the rolling process in a traditional Lagrangian finite element framework is by no means trivial. E.g. numerical issues arise when taking into account the continuously changing contact interface as the region moves relative to the discretized domain when the material passes between the rollers. In addition, complexity is added by the frictional stresses changing direction within a narrow sticking region for which the size and position is unknown in advance. All of these numerical issues are avoided in a steady-state framework by letting the discretized domain remain stationary relative to the rollers, while the sheet material passes through the domain. Thus, the contact interface, sticking region, and stress/strain fields become stationary to an observer at the rollers. This is all about relative motion, but the stationarity makes the numerical task easier to tackle.

Numerous numerical investigations of the rolling process have been undertaken and count both 1D, 2D and 3D studies (Montmitonnet, 2006). A large portion of these accepts rigid-plasticity or visco-plasticity as an approximation (Zienkiewicz et al., 1978; Mori et al., 1982; Cavaliere et al., 2001), and residual stresses and the associate material behaviour are typically

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neglected. Sheet rolling often takes place at elevated temperatures (hot rolling), ranking material sensitivity essential, but the importance of elastic unloading is recognized for rolling at room temperature (cold rolling). The steady-state formulation put forward by Dean and Hutchinson (1980) is well suitable for history dependent material deformation processes and it readily accounts for elastic unloading. Their method has been adapted to rolling in the study by Nielsen et al. (2015), and it will be further exploited in the present investigation. The objective of the present study is to gain insight into, and quantify, the combined effect of strain rate-sensitivity and strain gradient hardening during flat sheet rolling; essentially studying rate effects as the characteristic length scale reaches into the range where size effects become important. Both dissipative and energetic contributions are included.

The paper is structured as follows. The material model and steady-state formulation are presented in Section 2, while the considered boundary value problem is outlined in Section 3. Results are laid out in Section 4 and discussed with focus on the combined effect of strain rate-sensitivity and strain gradient hardening. Some concluding remarks are given in Section 5.

2. Model: constitutive relations and steady-state formulation

2.1. Rate-sensitive constitutive material model

The flat rolling problem is analyzed using the gradient enhanced elastic-viscoplastic material model proposed in Gudmundson (2004); Gurtin and Anand (2005); Fleck and Willis (2009). Here, a small strain formulation is employed. This is a reasonable approximation to the rolling process as the overall straining is proportional to the sheet reduction when limiting this to ~15%. For small sheet reductions, the strains and the rotations remain small – yet large plastic strain gradients can evolve (see e.g. Fig. 6). An additive decomposition of the total strain is applied, so that $\varepsilon_{ij} = \varepsilon_{ij}^e + \varepsilon_{ij}^p$, where ε_{ij}^e is the elastic part and ε_{ij}^p is the plastic part. The total strain field is determined from the displacements, which together with the plastic strain components are determined based on the principle of virtual work for the current higher order material. In Cartesian components, this reads

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

where q_{ij} is the micro-stress tensor, σ_{ij} is the Cauchy stress tensor, $s_{ij} = \sigma_{ij} - \delta_{ij}\sigma_{kk}/3$ is the stress deviator and τ_{ijk} is the higher order

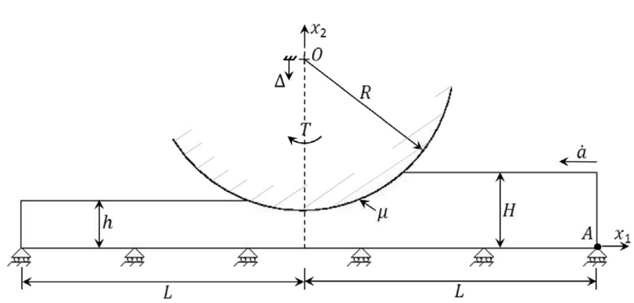

Fig. 1. Parameterization of the rolling process under steady-state conditions, with symmetry applied at $x_2 = 0$. Throughout, $L/H = 10$, with the domain discretized by equal sized squared elements of side length; $L^{(e)}/H = 20$, and unit thickness. Not shown is the width of the sheet in the out-of-plane direction, b.

stresses, work conjugate to the plastic strain gradients, $\varepsilon_{ij,k}^p$. Here, $(\ )_{,k}$ denotes the partial derivative with respect to the coordinate x_k. The right-hand side of Eq. (1) includes both conventional tractions, $T_i = \sigma_{ij}n_j$, and higher order tractions, $M_{ij} = \tau_{ijk}n_k$, with n_k denoting the outward normal to the surface S, which bounds the volume V.

Following Fleck and Willis (2009), the higher order stresses decompose into a dissipative part, τ_{ijk}^D, and a energetic part, τ_{ijk}^E, so that; $\tau_{ijk} = \tau_{ijk}^D + \tau_{ijk}^E$, whereas the micro-stress is assumed to have a dissipative part; $q_{ij} = q_{ij}^D$, only. The dissipative stress quantities read (Gudmundson, 2004; Fleck and Willis, 2009)

$$q_{ij}^D = \frac{2}{3}\frac{\sigma_C\left[\dot{E}^p, E^p\right]}{\dot{E}^p}\dot{\varepsilon}_{ij}^p, \quad \text{and} \quad \tau_{ijk}^D = \frac{\sigma_C\left[\dot{E}^p, E^p\right]}{\dot{E}^p}(L_D)^2\dot{\varepsilon}_{ij,k}^p \tag{2}$$

with the gradient enhanced effective stress identified as; $\sigma_C = \sqrt{3/2 q_{ij}^D q_{ij}^D + (L_D)^{-2}\tau_{ijk}^D\tau_{ijk}^D}$. The corresponding gradient enhanced effective plastic strain rate takes a quadratic form, so that

$$\dot{E}^p = \sqrt{\frac{2}{3}\dot{\varepsilon}_{ij}^p\dot{\varepsilon}_{ij}^p + (L_D)^2\dot{\varepsilon}_{ij,k}^p\dot{\varepsilon}_{ij,k}^p} \tag{3}$$

where, L_D is the dissipative length parameter introduced for dimensional consistency.

Plastic deformations are typically considered to be dissipative, covering irrecoverable heat energy and cold work, while no free energy is associated with the plastic strains. However, when large plastic strain gradients appear (Ashby, 1970), Geometrically Necessary Dislocations (GNDs) are develop, and this gives rise to additional free energy associated with the local stress field of the GNDs, as-well as increased dissipation when the GNDs move in the lattice (Gurtin, 2002; Ohno and Okumara, 2007). Thus, the total free energy takes the form

$$\Psi = \frac{1}{2}\left(\varepsilon_{ij} - \varepsilon_{ij}^p\right)\mathscr{L}_{ijkl}\left(\varepsilon_{kl} - \varepsilon_{kl}^p\right) + \Psi_G \tag{4}$$

where Ψ_G accounts for the free energy associated with GNDs. The conventional stresses is, thereby, given through the elastic relation; $\sigma_{ij} = \partial\Psi/\partial\varepsilon_{ij}^e = \mathscr{L}_{ijkl}(\varepsilon_{kl} - \varepsilon_{kl}^p)$, with $\mathscr{L}_{ijkl}$ being the isotropic elastic stiffness tensor, while the energetic higher order stresses are defined as; $\tau_{ijk}^E = \partial\Psi/\partial\varepsilon_{ij,k}^p$. The free energy related to GNDs are often assumed to be quadratic, with respect to the plastic strain gradients, so that; $\Psi_G = 1/2G(L_E)^2\varepsilon_{ij,k}^p\varepsilon_{ij,k}^p$. Thus the energetic higher order stresses read; $\tau_{ijk}^E = G(L_E)^2\varepsilon_{ij,k}^p$, where G is the elastic shear modulus and L_E is the energetic length parameter. This setup is employed throughout the present study, but it is recognized that an on-going discussion of the form of Ψ_G takes place in the literature (Fleck et al., 2015). In any case, it will become evident from the results that the energetic contribution has a negligible effect on sheet rolling.

The developed model rely on a power–law relation for the visco-plastic behaviour, so that

$$\dot{E}^p = \dot{\varepsilon}_0\left(\frac{\sigma_C}{g(E^p)}\right)^{1/m}, \quad \text{with} \quad g(E^p) = \sigma_y\left(1 + \frac{EE^p}{\sigma_y}\right)^N \tag{5}$$

where N is the power hardening exponent, m is the strain rate hardening exponent and $\dot{\varepsilon}_0$ is the reference strain rate. Thus, $\sigma_C[E^p, \dot{E}^p] = g(E^p)(\dot{E}^p/\dot{\varepsilon}_0)^m$. Thus, the developed model display significant visco-plastic behaviour for large strain rate hardening exponents, but approaches the response of a gradient enhanced J2-flow type material in the rate-independent limit ($m \to 0$, see e.g.

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