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A fully-coupled approach combining plastic deformation and liquid lubrication

Esmeray Üstünyagiz^{1,a}, Peter Christiansen¹, Chris V. Nielsen¹, Niels Bay¹ and Paulo A.F. Martins²

¹Department of Mechanical Engineering, Technical University of Denmark, 2800 Kgs. Lyngby, Denmark

²IDMEC, Instituto Superior Tecnico, Universidade de Lisboa, Portugal, 1049-001 Lisbon, Portugal

Abstract. This paper presents a new approach based on a fully coupled procedure in which the lubricant flow and the plastic deformation of the metallic material are solved simultaneously. The approach is applied to strip reduction of a sheet with surface pockets in order to investigate the escape of the lubricant from the pocket by means of Micro Plasto HydroDynamic Lubrication (MPHDL) and Micro Plasto HydroStatic Lubrication (MPHSL) mechanisms.

1 Introduction

In most of the metal forming processes the liquid lubrication regime is characterized by mixed-film lubrication, in which the interface pressure is carried partly by the pressurized lubricant trapped in surface pockets and partly by asperity contact. These conditions are known to have a considerably influence on the friction, wear and surface topography.

Early studies on the influence of the entrapped lubricant on the real contact area [1], were followed by Mizuno and Okamoto's proposal of the Mechanism of Micro Plasto HydroDynamic Lubrication (MPHDL) [2]. The theory was later verified by Kudo et al. [3] and Azushima et al. [4] who performed strip drawing test through a wedge shaped, transparent die and observed the lubricant escape from the initially indented pockets directly. Subsequently, Bech et al. [5] used the same testing set-up to investigate the effect of various parameters on the escape mechanism.

In numerical modelling of metal forming processes it is, however, still the current practice to model friction by either Coulomb's law or the law of constant friction stress without taking the broad range of parameters influencing friction e.g. surface expansion, sliding speed, lubricant viscosity and surface topography into account.

Very recently, Carretta et al. [6] made a breakthrough by combining computational fluid dynamics and solid mechanics to analyse the mechanism of micro-plasto-hydrodynamic lubrication. Their methodology proved, however, difficulties due to the differences of 9-10 orders of magnitude in stiffness between the metal and fluid. Besides that, typical implementations of the Navier-Stokes equations in computational fluid dynamics work with velocities and pressures, whereas commonly utilized solid mechanics formulations work with displacements.

This paper is built upon an alternative fully-coupled approach for modelling the interaction between plastic deformation and liquid lubrication that was proposed by the authors [7]. The approach is based on the finite element flow formulation [8] that allows treating metals as non-Newtonian, high viscous, incompressible fluids and lubricants as viscous, Newtonian fluids. The developed model is applied to in-plane strip reduction tests in order to analyse the escape of entrapped lubricant by Micro Plasto HydroDynamic Lubrication (MPHDL) and Micro Plasto HydroStatic Lubrication (MPHSL). A parametric study of friction factor and shear viscosity is carried out to show the trend of MPHSL and MPHDL, respectively. Numerical predictions are compared with experimental results provided by Bech et al. [5].

2 Theoretical background

For any fluid satisfying the continuum assumption the differential equation of linear momentum resulting from force equilibrium in a fluid particle is given by

$$\frac{\partial \sigma'_{ij}}{\partial x_j} - \frac{\partial p}{\partial x_i} + \rho g_i = \rho \left(\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} \right). \quad (1)$$

The terms on the left-hand side of Eq. 1 are related to viscous forces, pressure and gravity respectively, the sum of the mean stress σ_m and the viscous (or deviatoric) stresses σ'_{ij} gives the total stresses σ_{ij} . The right-hand side of Eq. 1 represents the inertia effects where the term inside the brackets is the total derivative of the velocity vector, i.e., acceleration a_i . If the convective terms of the total derivative are neglected, and if the viscous stresses σ'_{ij} are assumed to be proportional to strain rates $\dot{\epsilon}'_{ij}$, i.e., $\sigma'_{ij} = 2\mu \dot{\epsilon}'_{ij}$, the differential equation of

^a Corresponding author: esustu@mek.dtu.dk

motion for incompressible flow with constant viscosity reduces to the so called Navier-Stokes equation,

$$\mu_s \frac{\partial^2 u_i}{\partial x_j^2} - \frac{\partial p}{\partial x_i} + \rho g_i = \rho \frac{du_i}{dt} \quad (2)$$

where μ_s is the shear viscosity, which takes constant values $\mu_s = \mu_{0,s}$ for Newtonian fluids and strain rate dependent values $\mu_s = \mu_{0,s}(\dot{\epsilon}_{ij})$ for non-Newtonian fluids.

If the elastic response of metals as well as the inertia effects are neglected, the above expression becomes identical to the flow formulation. The basis for coupling the plastic flow of metals and the incompressible laminar flow of viscous fluids lies in the fact that the flow formulation treats metals as rigid-plastic (or rigid-viscoplastic) materials that fulfill the incompressibility condition $\dot{\epsilon}_{ii} = 0$.

The irreducible finite element flow formulation is derived from the discretization of the weak form of Eq. 2 by means of finite elements, as follows

$$\int_V \sigma'_{ij} \delta \dot{\epsilon}'_{ij} dV + K \int_V \dot{\epsilon}_{ii} \delta \dot{\epsilon}_{ii} dV - \int_{S_T} t_i \delta u_i dS + \int_V \rho g_i \delta u_i dV = 0. \quad (3)$$

The separation between deviatoric and volumetric terms that exists both in the differential equation of linear momentum and the flow formulation, enables a direct correlation between the shear and bulk viscosities of metals and fluids. The deviatoric (viscous) stresses of metals, for example, may be seen as the stress response of non-Newtonian fluids of very high viscosity μ_s (in close analogy to $\sigma'_{ij} = 2\mu \dot{\epsilon}'_{ij}$),

$$\sigma'_{ij} = \frac{2}{3} \frac{\bar{\sigma}}{\bar{\epsilon}} \dot{\epsilon}'_{ij}. \quad (4)$$

Conversely, the penalty factor K of metals that is utilized to ensure the incompressibility of plastic flow, is similar to the bulk viscosity μ_v of the liquids,

$$\sigma_m = -p = K \dot{\epsilon}_{ii} \quad \& \quad K = \mu_v. \quad (5)$$

The above mentioned analogy between the plastic flow of metals and the laminar flow of viscous fluids is the basis of the proposed fully-coupled approach in which velocities and hydrostatic pressures are solved simultaneously.

3 Numerical model

Depending on various parameters the lubricant may escape either forward by Micro Plasto HydroStatic Lubrication (MPHSL) or backwards by Micro Plasto Hydrodynamic Lubrication (MPHDL), see Fig. 1. The forward escape occurs when the lubricant pressure p_{liq} reaches the sealing pressure p_f at the front end of the pocket. The backward escape occurs when the viscous drag of the lubricant creates a liquid pressure at the rear end of the pocket reaching the sealing pressure at the back of the pocket.

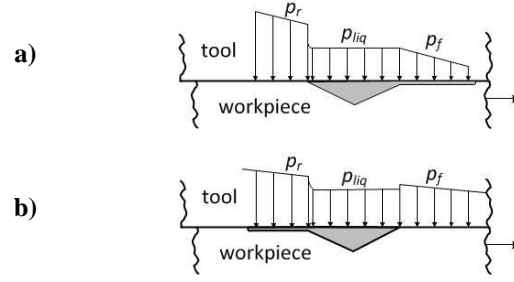


Figure 1. Schematic of the two mechanisms of lubricant escape. a) Micro Plasto HydroStatic Lubrication; b) Micro Plasto HydroDynamic Lubrication.

The assessment of the proposed fully-coupled numerical approach makes use of experimental data provided by Bech et al. [5]. The referred study indicates that an increase of die friction leads to a shift from backward towards forward escape, whereas increasing viscosity leads to the opposite trend [5]. In contrast to the MPHSL mechanism that gives rise to a sudden escape and corresponding pressure drop of the lubricant, the MPHDL mechanism is caused by viscous drag forces and therefore it can be regarded as a continuous process.

The model utilized by the authors consists of a strip drawing operation with a semi-die angle of 5° and a reduction of 15%. The 2 mm thick sheet was provided with a pocket of 1x1mm base length and 10° slope, Fig.2. The bulk viscosity was kept constant $\mu_v = 1500$ MPa.s. The sheet material was an aluminium alloy [5] with a stress-strain curve $\bar{\sigma} = 321 \bar{\epsilon}^{0.08}$ MPa. Sticking friction was imposed along the contact interfaces between the lubricant and the strip and a constant friction factor $m = 0.3$ was used for the contact with the upper die.

The sheet and lubricant were discretized by linear quadrilateral elements under plane strain deformation conditions. The dies were treated as rigid bodies and discretized by linear contact elements. Under these modelling conditions a simulation consisting of a mesh with approximately 9300 nodal points and 9100 elements ran approximately 4 hours in a computer equipped with an Intel CPU e5-1660 (3.0 GHz) processor.

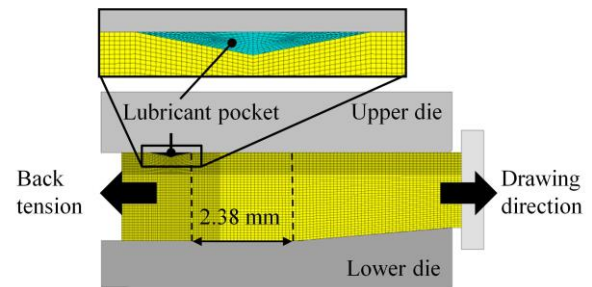


Figure 2. Finite element model of strip drawing with a detail of the pocket on the strip surface.

4 Results

For the identification of forward escape the parametric study concerned friction conditions between the inclined

lower tool and the strip materials. The shear viscosity was kept constant $\mu_{s,0} = 0.1$ Pa·s. The drawing speed was $v = 0.2$ mm/s.

Fig. 3 shows the increase of pressure with displacement for two test cases with friction factors $m = 0$ and $m = 0.3$. After the lubricant pocket enters the deformation zone, the liquid pressure increases within the pocket. Increased friction on the lower die leads to a decrease in the sealing pressure at the front end of the pocket. Consequently, the lubricant pressure reaches the sealing pressure, thereby promoting the MPHSL mechanism as observed experimentally by Bech [5].

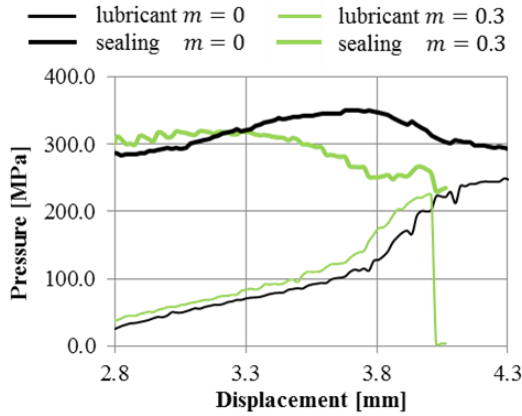


Figure 3. Evaluation of the liquid pressure and the front sealing pressure of the pocket with respect to displacement.

To investigate the backward escape with the proposed approach, various shear viscosity values were utilized. The lower die friction was set to $m = 0$ and the drawing speed was $v = 0.5$ mm/s. The analysis of escape, due to local pressure increase at the rear edge of the pocket, was constrained by numerical difficulties derived from unacceptable distortion of the liquid mesh. Therefore, numerical modelling of the sealing pressure and the liquid pressure versus the displacement of the pocket was combined with an analytical model of the liquid pressure increase in the converging gap at the rear end of the pocket. The analytical model was the same as that proposed earlier by Bech et al. [5] by using Reynold's equation:

$$\frac{dp_{liq}}{dx} = 6\mu_s v \frac{h - h_m}{h^3} \quad (\text{MPa}) \quad (6)$$

where p_{liq} is the local hydrostatic lubricant pressure, h is the local film thickness, h_m is the film thickness in the plateau and v is the sliding velocity. μ_s is the pressure dependent viscosity described as $\mu_s = \mu_{s,0} \exp(\alpha p_{liq})$ where $\mu_{s,0} = 0.005; 0.76$ and 1.0 Pa·s respectively and the pressure-viscosity coefficient is $\alpha = 2.1 \times 10^{-8}$. In the analysis, the pocket edge radius of curvature was $R = 80$ μm and the film thickness was $h_m = 0.1$ μm .

Fig. 4 illustrates the calculated liquid pressure in the pocket and rear sealing pressure with respect to displacement. It is concluded that the sealing pressure

was not reached for $\mu_{s,0} = 0.76$ Pa·s (Fig. 4). However, if the viscosity is raised to $\mu_{s,0} = 1.5$ Pa·s the liquid pressure exceeds the sealing pressure and the MPHDL is triggered.

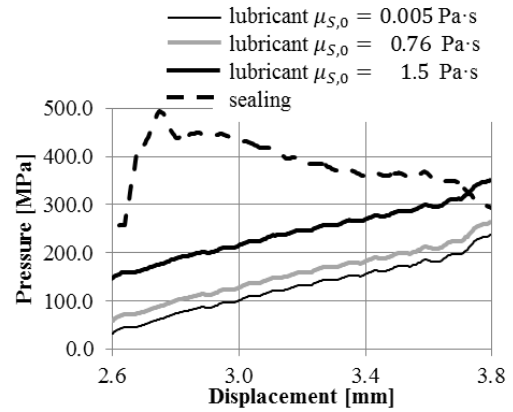


Figure 4. Evaluation of the liquid pressure and the rear sealing pressure of the pocket with respect to displacement.

5 Summary

The proposed approach was successfully applied to strip reduction tests investigating the MPHSL and MPHDL mechanisms. Varying operative conditions for both MPHSL and MPHDL mechanisms were investigated by changing lower die friction and shear viscosity respectively. The results compared well with previous experimental observations obtained by Bech et al. [5].

Current limitations in the computer implementation of the proposed fully-coupled approach do not allow replicating the physical escape of the lubricant which requires a call for further improvements.

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