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A Weakly Coupled Fluid Solid Interaction Approach for Hydrostatic Pressure Build-Up in Metal Processing

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Abstract

This paper presents a new modelling approach for liquid lubricant behavior in metal forming operations by focusing on the hydrodynamic pressure build-up in micro pockets. Theoretical and numerical fundamentals of the proposed approach are introduced, and upsetting of an aluminum cylinder with an artificial lubricant pocket is presented as a validation case. The proposed numerical framework splits the fluid-solid interaction model into a computational fluid dynamics and solid mechanics part. While the solid mechanics part employs the Lagrangian finite element flow formulation for plastic deformation, the fluid dynamics part is built upon the set of Navier-Stokes equations applying an Eulerian finite element method in combination with an Arbitrary Lagrangian Eulerian formalism. The latter enables the displacement based coupling from the solid to the fluid. The fluid-to-solid coupling is pressure based and enabled by the finite element flow formulation’s inherent velocity-pressure characteristics. The weak coupling avoids ill-conditioning of the system matrix and makes it possible to benefit from both Lagrangian and Eulerian meshes.

Keywords: Sheet Metal Forming; Fluid Solid Interaction; Finite Element Flow Formulation; Computational Fluid Dynamics; Hydrodynamic Lubrication

1. Introduction

Large scale production of metal parts is an integral part of today’s manufacturing landscape and can be seen in many different industries, as the automotive or aerospace industry for instance. Whether sheet or bulk metal forming, the processes have the inherent problem that in-situ observations are not possible. This becomes challenging when designing the process and the application of liquid lubrication, which avoids wear at both the workpieces and the tools. The behaviour of the lubricant during such processes is to a large extend unpredictable and thus sufficient lubrication can often only be ensured by excess lubrication which, among others, results in high consumption and required cleaning of the workpieces afterwards.

When liquid lubrication is applied to metal forming processes, the lubrication is often in the mixed lubrication regime. Here, the interface pressure is partially carried by asperities in metal-metal contact and partially by pressurised lubricant entrapped in micro-pockets at the contact interface. The great load carrying capacity of the entrapped lubricant was pointed out by Kudo [1] and Wanheim [2]. If the hydrostatic pressure in the micro-pocket exceeds the sealing pressure, i.e. the contact pressure between the two metal surfaces, the lubricant will escape. This escape is known as Micro-Plasto HydroStatic Lubrication (MPHSL). Mizuno and Okamoto [3] found that lubricants dynamically escape from micro-pockets, when the two surfaces in contact were moved relative to each other. The observed phenomenon was designated as Micro-Plasto HydroDynamic Lubrication (MPHDL) and later confirmed by Azushima et al. [4–7] by direct observations of the effect occurring in plane strip drawing of aluminium strips through a transparent die and a microscope-camera set-up. Further experimental research on hydrodynamic lubrication was conducted in several studies by Bech et al. [8, 9], Sørensen et al. [10], Shimizu et al. [11], Lo and Horng [12], and Ahmed and Sutcliffe [13].
As mentioned, the behaviour of the lubricant cannot be observed in-situ and thus the above effects can barely be controlled or used for optimisation. It is desirable to utilize both MPHSL and MPHDL such that workpieces can be tailored towards optimal lubrication behaviour along the entire process. This could be realised through applying artificial grooves to the workpiece surface which would act as a lubricant reservoirs. These grooves would be flattened at the desired point of the process and the squeezed out lubricant would re-lubricate the workpiece-tool interface. Due to the inherent unobservability of this behaviour this may only be achieved through numerical simulations.

Unlike the experimental work, there are only few numerical studies on the hydrodynamic lubrication mechanisms. Hydrostatic pressure build-up in artificial lubricant pockets during upsetting of a cylinder was numerically investigated by Azushima [14] and Sulaiman et al. [15], among others. MPHSL and MPHDL were investigated by Üstünyagiz et al. [16, 17] by simulating plane strip drawing with a fully coupled fluid-solid interaction approach by employing a rigid-viscoplastic finite-element formulation. Hydrostatic pressure build-up during strip-drawing could be simulated, whereas the MPHDL mechanism was only analytically added. Carretta et al. [18, 19] employed a solid mechanics finite element program and treated the lubricant as a Newtonian fluid by means of the Norton-Hoff material law. They were able to simulate the MPHDL onset and escape behaviour of the lubricant in artificial micro-pockets during strip-drawing. During the above-mentioned studies, it was realised that the distinct differences in stiffness of a metal and a fluid and large differences in element area due to distinctly differently sized features in the model cause ill-conditioning of the system matrix. The low stiffness of the fluid also caused mesh distortion as it moves faster than the metal, which was solved by Carretta et al. [18, 19] by employing an Arbitrary Lagrangian Eulerian formalism, where the fluid and metal meshes were uncoupled.

The presented approach is a weak coupling of the lubricant and metal flows. The fluid flow is governed by the Navier-Stokes equations and solved by a computational fluid dynamics (CFD) solver, working with pressures and velocities. The plastic flow of the metal is based on the irreducible flow formulation with its inherent velocity-pressure characteristics. The latter may be chosen when it comes to simulating forming operations, as the flow of a metal essentially resembles the flow of a fluid [20]. Additionally, its velocity-pressure characteristic enables a seamless communication with a Navier-Stokes equations solver as both are driven by velocities and pressures. The two models are weakly coupled, which avoids ill-conditioning of the system matrix and mesh distortion of the fluid mesh. Additionally, the approach enables a more realistic treatment of the lubricants, which behaves non-linear in terms of density and viscosity, as both are considerably pressure dependent [21]. The numerical model is validated against the experimental results of Sulaiman et al. [15] that describe the hydrostatic pressure build-up of a compressible lubricant in an artificial lubricant pocket during upsetting of a cylinder.

2. Validation case

Upsetting of a cylinder with an artificial lubricant pocket was chosen as an initial validation case for the proposed numerical coupling of the solid and fluid models. Sulaiman et al. [15] investigated upsetting of a cylinder where the set-up is schematically depicted in Figure 1(a). The workpiece was manufactured of aluminium 1050 and the applied lubricant was CR5 by Houghton with a density \( \rho = 920 \text{ kg/m}^3 \) at ambient pressure and a pressure dependent density as shown in Figure 1 (b). They conducted upsetting up to a reduction of 56% while applying a die velocity \( v = 0.1 \text{ mm/s} \). Subsequently, the contour of the pocket was measured at 16%, 27% and 56% reduction, which was used to validate the presented numerical coupling.

3. Numerical Framework

3.1. Governing Equations

The flow of a metal may be governed by the irreducible flow formulation shown in Eq. (1) in its weak form.

\[
\Pi = \int_V \bar{\sigma} \bar{\varepsilon} dV + \frac{1}{2} K \int_V \bar{\varepsilon}^2 dV - \int_{S_T} T_{ij} u_i dS + \int_{S_f} \left( \int_0^{s^{1/2}} \tau_{ij} d\sigma \right) dS
\]  

Figure 1: Validation case: (a) schematic presentation of the experimental set-up after Sulaiman et al. [15] and (b) pressure dependent density based on experimental results by Sulaiman [22].
Here, \( \sigma \) is the effective stress, \( \dot{\varepsilon} \) the effective strain rate, \( K \) a large positive constant enforcing the incompressibility, \( \dot{\varepsilon}_V \) the volumetric strain rate, and \( V \) the volume. The surface traction \( T_i \) and the velocities \( u_i \) are defined on the surface \( S_T \). The last term in Eq. (1) represents the contact surface \( S_f \) between tool and workpiece where \( \tau_f \) is the friction shear stress and \( u_r \) is the relative sliding velocity. The governing equation is numerically approximated by means of the finite element method (FEM) on a Lagrangian mesh discretised in space by quadrilateral elements with four nodes. The employed FEM software is the in-house software i-form2. Further information may be found in [23].

The lubricant is treated as a compressible Newtonian fluid, which is governed by the compressible Navier-Stokes equations. Since the flow is assumed to be laminar and creeping, i.e. Reynold’s numbers of \( Re<1 \), the governing Navier-Stokes equations simplify to the continuity equation in Eq. (2) and the momentum equation in Eq. (3).

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \tag{2}
\]
\[
\rho \frac{\partial \mathbf{u}}{\partial t} = \nabla \cdot (-pI + \mu(\nabla \mathbf{u} + (\nabla \mathbf{u})^T) - \frac{2}{3} \mu(\nabla \cdot \mathbf{u})I) + \mathbf{F} \tag{3}
\]
In Eq. (2) and Eq. (3), \( \rho \) is the pressure dependent fluid density, \( \mathbf{u} \) the velocity vector, \( t \) the time, \( \nabla \) the Nabla operator, \( \mu \) the dynamic viscosity, \( \mathbf{I} \) the identity matrix and \( \mathbf{F} \) the volume force vector. The governing equations are numerically approximated by the finite element method on an Eulerian mesh discretised into quadrilateral elements in the software Comsol Multiphysics 5.4 [24]. Since not only the deformation of the metal but also the fluid domain is considered, the fluid domain was modelled such that it can be updated between time steps, which was realised by means of an Arbitrary Lagrangian Eulerian formalism.

3.2. Coupling

The workflow of the weak coupling of the two numerical models is depicted in Figure 2. At first, the metal flow simulation is executed for an incremental time step \( \Delta t \). The resulting displacement of the interface between the liquid and solid is transferred to the CFD software, where the deformation of the mesh is updated. Secondly, the lubricant flow simulation of the \( i \)th step is run with the updated fluid-solid interface deformation. After the \( i \)th step has finished, the pressure along fluid-solid interface is transferred to the metal flow simulation, where it is applied as a pressure boundary condition along the interface in the \((i+1)\)th step. The procedure is repeated until the specified total deformation is achieved.

3.3. Numerical Model

The numerical model was designed in accordance with the experimental set-up by Sulaiman et al. [1] shown in Figure 1(a). The simulations were performed in two axisymmetric models, where the lubricant was discretised into 248 elements and the workpiece into 940 elements. The global time step was \( \Delta t=0.01 \)s in iForm, while Comsol further divides it into sub-steps. The metal obeyed a Hollomon flow stress curve, presented in Figure 1(a), and the lubricant’s pressure dependent density was defined according to the relation shown in Figure 1(b).

The friction between dies and workpiece was modelled according to the Coulomb law of friction \( \tau = \mu_f \mathbf{p} \), where \( \tau \) is the friction stress, \( \mu_f \) the coefficient of friction and \( \mathbf{p} \) the normal pressure. This friction law is justified by the ratio between normal pressure and flow stress to be in the range of around 1-1.3. At the contact between the lower die and the workpiece, friction was neglected due to the Teflon layer.

4. Results

A numerical study was conducted while the friction coefficient \( \mu_f \) between the upper die and workpiece was varied. The simulation gave a best fit to experimental results with \( \mu_f = 0.18 \), which is presented in Figure 3(a) – (c). Variation of the friction coefficient \( \mu_f \) is shown in Figure 4. The model shows a sensitivity towards a variation of the friction coefficient, which increases with the reduction. In Figure 4(c), the pocket opening is seen to overshoot or undershoot the experimental pocket opening when a too low or too high friction coefficient is applied, respectively. Figure 5(d) compares the experimental and numerical load-displacement curves throughout the upsetting, which are in good agreement. Figure 5(a) plots the hydrostatic pressure build-up as a function of the reduction. An initial overshooting of the pressure is noticed. This may be due to the sudden initial movement of the fluid domain boundary or the very limited flow in the CFD calculations. Figure 5(b) shows a reduction of the overshooting by reducing the global time step by a factor of 10. Further convergence studies of the time step will be performed to understand the initial pressure build-up.

5. Conclusion

The presented weakly coupled fluid-solid interaction approach showed good results for simulations of upsetting of a cylinder with an artificial lubricant pocket. The approach was capable of modelling the load carrying capacity of a compressible lubricant, its non-linear behaviour and its interaction with the non-linear metal deformation. Additionally, one may recognise that the presented model only required adjustment of the coefficient of friction, since the material behaviour of both lubricant and metal were experimentally determined in the work by Sulaiman et al. [15] and [23].

The proposed model avoids mesh distortion and large differences in the stiffness matrix due to the weak coupling. This is important for future calculations involving more lubricant flow in metal forming processes. The aim is to simulate micro-plasto hydrodynamic lubrication involving
both lubricant entrapment and subsequent lubricant escape. In the long run, it may be possible to tailor metal surfaces such that both effects can be utilized to improve metal forming processes through numerical simulations.

Figure 5: Hydrostatic pressure build up (a) as function of the reduction and (b) the influence of time step on the numerical overshooting of the pressure

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