

A SOFTWARE SOLUTION FOR ADVANCED FRICTION MODELING APPLIED TO SHEET METAL FORMING

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ABSTRACT: In this paper, a software solution is presented for advanced friction modeling in metal forming processes, using a physically-based friction model. As input, the model requires the properties of the metal-lubricant combination used and the surface characteristics of the tooling and sheet material. As output, the friction coefficient is provided in both the boundary and mixed lubrication regime. This includes the effect of surface changes due to normal loading, sliding and straining the underlying bulk material. Adhesion and ploughing effects are accounted for to characterize friction conditions on the micro scale. To account for lubrication, hydrodynamic contact elements have been developed and integrated in the software. Pressure degrees of freedom are introduced to capture the pressure values which are computed by a finite element discretization of the 2D averaged Reynolds equation. The boundary friction model and the hydrodynamic friction model have been coupled to cover the mixed lubrication regime. The software solution, provided by Innprove Solutions, is coupled to commercial finite element packages enabling advanced friction modeling for sheet metal forming.

KEYWORDS: Tribological and friction modeling, boundary and mixed lubrication, sheet metal forming

1 INTRODUCTION

Finite Element simulations of sheet metal forming processes are everyday practice in many industries. The accuracy of Finite Element (FE) simulations depends on, amongst others, friction modeling. In the majority of simulations still the Coulomb friction model is used. However, it is known that the true physical tribological conditions are dependent on local process and lubrication conditions, loading and local strain state [1-3].

In the boundary lubrication regime, friction is mainly caused by adhesion and ploughing between contacting asperities. The real area of contact, playing an important role in characterizing friction, relies on the roughness characteristics of both the tool and the sheet surface. The roughness of the sheet is influenced by flattening and roughening mechanisms. The main flattening mechanisms during sheet metal forming, which tend to increase the real area of contact, are flattening due to normal loading, flattening due to combined normal loading and straining the underlying bulk material and sliding. Roughening of asperities, which is observed during deformation of the bulk material without applying a normal load to the surface, tends to decrease the real area of contact.

For lubricated forming processes, contact conditions could also occur in the mixed lubrication regime. Hence, it is important to account for the hydrodynamic action present in the lubricant as well, for which the velocity difference between mating surfaces and the temperature at the interface becomes important. Since different contact conditions occur during metal forming, different contact zones can act in different lubrication regimes.

The software solution presented in this paper, referred to as the TriMM software, allows for the modeling of a time and locally varying friction coefficient under a wide range of process conditions. A coupling between the implemented boundary lubrication friction model and a hydrodynamic friction model is made based on the lubricant film thickness [4,5]. Mixed lubrication interface elements are introduced to solve the governing differential equations. The frictional behavior can now be calculated as a function of the local pressure and the velocity difference between mating surfaces, the temperature at the interface, and the strain in the sheet material. The presented software solution also enables the calculation of friction coefficients for process conditions which cannot be evaluated using friction experiments, e.g. for higher pressures. The latter is especially

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important for correctly determining and modeling the frictional behavior in draw beads and radii.

A coupling has been made with commercial FE packages, enabling advanced friction modeling while minimally influencing the computation time. Since the software makes use of the measured surface characteristics of the tooling and sheet material, also anisotropic friction, regional dependent friction and the products surface quality after forming can be predicted.

TriMM is based on the framework as described in this paper. FE simulations have been carried out including the advanced friction model for a sheet metal forming process, i.e. the forming of a top hat section. In addition, experimental validation of the numerical results was performed as discussed in the final section.

2 MODELING APPROACH

The modeling software TriMM comprises four stages, see Figure 1. Existing, adapted and newly developed models have been implemented within this framework. The result is a physically based friction model that is still computationally attractive for use in sheet metal forming simulations.

2.1 Stage 1: Input step

In the first stage, the input step, the characteristics of the used metal-lubricant combination are defined. See Figure 1. Next to the material properties of the sheet material and the type of tooling material and lubricant used, also the 3-dimensional surface textures of both tool and sheet material are read-in. Using confocal microscopy measurements, the surface properties can be characterized and stochastic variables are determined. For the lubricant, the viscosity and amount of lubricant applied is of importance. Moreover, a relation describing the boundary layer shear strength of the interface is required, which can be obtained by a surface force apparatus. Finally, results of sliding experiments are required to obtain a relation between the nominal contact pressure and the real area of contact, which is used to calibrate the incorporated micro-mechanical friction models. An experimental procedure to obtain the required input data is discussed in detail in [4].

2.2 Stage 2: Boundary lubrication model

The boundary lubrication model includes models to describe the change in tribological properties during forming due to normal loading, deformation of the underlying bulk material and sliding. The models provide an expression for the fractional real contact area under the assumption of a flat tool surface and a rough sheet surface. The non-linear work-hardening model as proposed by Hol et al. in [4] has been implemented to describe the

deformation of asperities due to normal loading. Asperity flattening due to combined normal loading and deformation of the underlying bulk material has been described by the flattening model proposed by Westeneng [6]. The increase in real contact area due to sliding is captured by adopting the junction growth theory as proposed by Tabor [7]. The influence of ploughing and adhesion on friction is accounted for by using the contact model of Ma et al. [8]. This model was originally developed to describe friction in extrusion processes, but has been adapted to model friction in sheet metal forming processes. For this purpose, the plateaus of the flattened asperities of the sheet material are assumed to be perfectly flat, in which tool contact patches (a collection of neighboring tool asperities that are in contact) are penetrating. The contact model of Ma et al. has been coupled to the friction model of Challen and Oxley [9] to calculate friction forces on individual contact patches. The boundary shear stress τ_{asp} can finally be obtained by adding the individual contributions of all contacting tool patches:

$$\tau_{asp} = \frac{F_w}{A_{nom}} = \frac{\sum_{i=1}^m \mu_i(\theta_{eff}) A_i H}{A_{nom}} \quad (1)$$

with θ_{eff} the effective attack angle of a contact patch, A_i the contact area of the contact patch and H the hardness of the material. As a result, the frictional behavior in the boundary-lubrication regime can be described.

2.3 Stage 3: Mixed lubrication model

The calculated deformation of asperities of the sheet material is used to calculate the volume of the lubricant entrapped into non-contact surface pockets. This information is subsequently used to calculate the fluid film thickness h , required to calculate the lubricant film pressure p_{lub} :

$$h = \frac{\int_{-\infty}^{d-U} (d - U - z) \phi_w(z) dz}{\int_{-\infty}^{d-U} \phi_w(z) dz} \quad (2)$$

In which d represents the amount of asperity deformation, U the amount of rise of non-contacting asperities and ϕ_w the surface height distribution of the sheet material, see Figure 2.

The mixed lubrication model comprises a coupling between the boundary lubrication model (stage 2) and the hydrodynamic friction model as proposed by Patir & Cheng in [10].

To solve the hydrodynamic pressure distribution, an FE approach has been adopted as described in [5], introducing hydrodynamic contact elements with additional pressure degrees of freedom. Viscous shear stresses at the fluid–solid interfaces

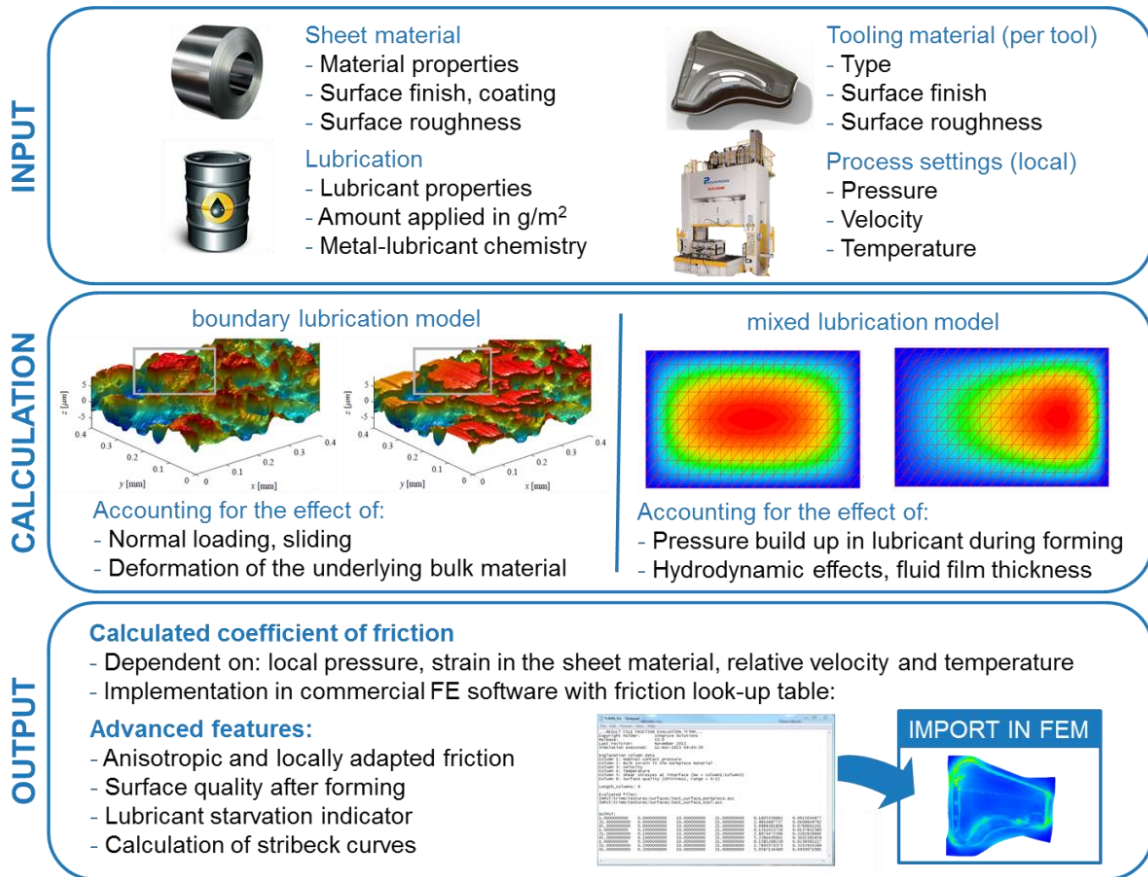


Fig. 1: Tribological modeling in FEM

are calculated based on the obtained hydrodynamic pressure distribution:

$$\tau = \frac{\eta(\mathbf{v}_1 - \mathbf{v}_2)}{h} + \frac{2z - h}{2} \nabla p_{lub} \quad (3)$$

with $\boldsymbol{\tau} = (\tau_{xy}, \tau_{yz})$ the shear stress as a function of the height z (at a specific xy -location). The summation of shear forces acting between contacting surface asperities and at the fluid-solid interface (viscous shear stresses) is used to obtain the friction coefficient, see Equation 4.

$$\mu = \frac{\tau_{asp} + \tau_{lub}}{P_{nom}} \quad (4)$$

With $\tau_{lub} = \sqrt{\tau_{xy}^2 + \tau_{yz}^2}$. As a result, the frictional behavior in the mixed-lubrication regime can be described.

2.4 Stage 4: Coupling with FE software

The presented software solution for advanced friction modeling has been coupled with an FE software code. That is, for each time increment and for each node in contact, a friction coefficient is calculated. For the boundary lubrication model, a look-up table is constructed for a predefined range of nominal contact pressures exerted on the surface and strains occurring in the bulk material. This look-up table contains information regarding the friction coefficient, surface deformation and surface quality, and is used as such in an FE simulation to guarantee computational efficiency. An additional advantage of this approach is the possibility to generate friction tables for specific metal-lubricant combinations. A friction table has to be constructed only once for such a specific combination, after which it can be used to describe friction in different FE forming simulations where this combination is used. The look-up table as generated by TriMM can be coupled to different commercially available FE packages, see Figure 1.

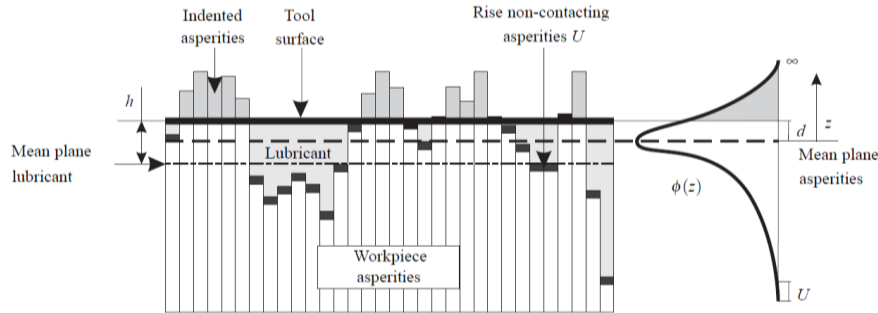


Figure 2: A rough soft surface crushed by a hard smooth tool

To model mixed lubrication in FE forming simulations, the hydrodynamic contact elements as discussed in Section 2.3 have been implemented in an FE software code. The coupling between the boundary lubrication model and the hydrodynamic model, by making use of the fluid film thickness h , enables the prediction of mixed lubrication friction in full-scale FE forming simulations. Instead of using hydrodynamic elements, mixed-lubrication friction modeling can be performed using a look-up table that contains additional information on the effect of lubrication on the friction coefficient. For this purpose, the influence of hydrodynamic effects on the friction coefficient is calculated for a predefined set of conditions, i.e. size of the contact zone, velocity and pressure distribution within the contact zone. As for the boundary lubrication case, the constructed friction table holds for a specific metal-lubricant combination and can be coupled to different commercially available FE packages.

3 Application Top-hat section

To demonstrate the performance of the presented software solution for advanced friction modeling, a comparison has been made between experiments and simulations. Experiments on a top-hat section (see Figure 3a) have been conducted using DC06 steel material lubricated with the Quaker Prelube FERROCOAT® N6130 and with the high viscosity Prelube Fuchs Anticorit PLS100T. Different blankholder forces and lubrication

amounts have been tested by using a stroke distance of 75 mm and a punch velocity of 20 mm/s and 50 mm/s. The strip geometry is 300x25x0.8 mm.

Figure 3b shows a contour plot of the carrying capacity of the lubricant at 75 mm punch stroke. Results are shown for the side of the blank in contact with the die. A lubricant pressure is observed near the die shoulder. When the strip slides over the die-shoulder, severe asperity flattening takes place due to the high increase in nominal contact pressures. The variation in contact pressure between the die and the strip generates a converging wedge in deformed asperities. This converging wedge supports the carrying capacity of the lubricant in this area. Lubricant pressures up to 40 MPa are found within this area, meaning that almost full-film lubrication takes place. As can be seen, the lubricant carrying capacity is symmetric through the center line of the strip and reduces to zero towards the free edges, showing a correct handling of the boundary conditions applied to the FE simulation.

The influence of the lubricant carrying capacity on the friction coefficient is shown in Figure 3c. If the lubricant pressure equals zero, the friction coefficient is dominated by boundary lubrication friction. The influence of the lubricant carrying capacity on the friction coefficient is clearly visible. If the friction coefficient drops to values around 0.02, the friction regime shifts towards the full-film lubrication regime. Boundary friction

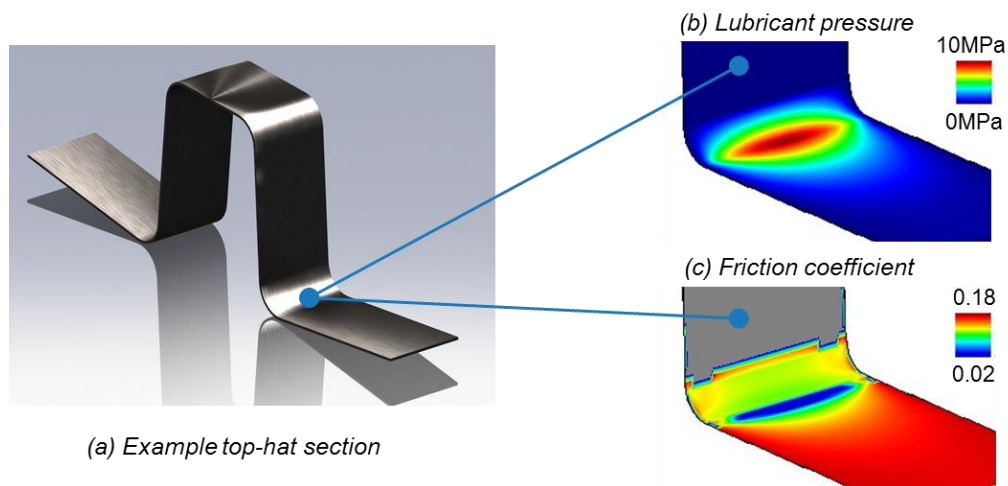


Figure 3: Example top-hat section and contour figures lubricant pressure build up and friction coefficients.

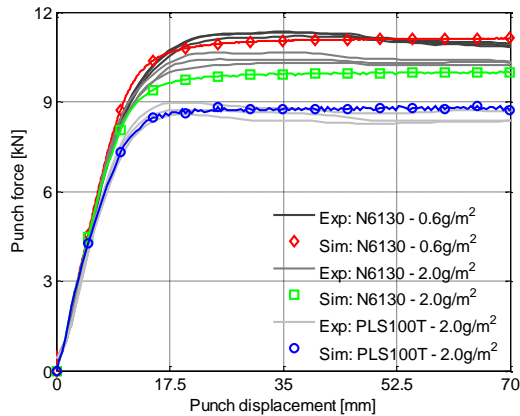


Fig. 4: Experimental and numerical punch force displacement-diagrams by using the advanced friction model

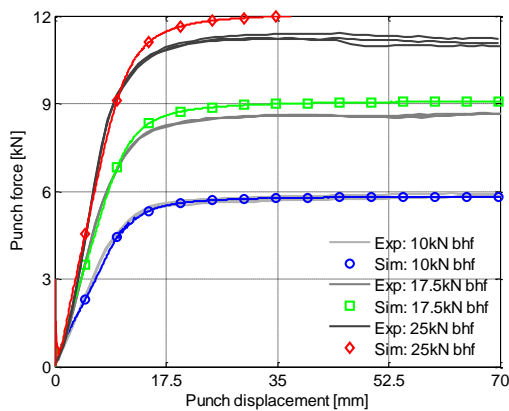


Fig. 5: Experimental and numerical punch force displacement-diagrams by using the Coulomb friction model

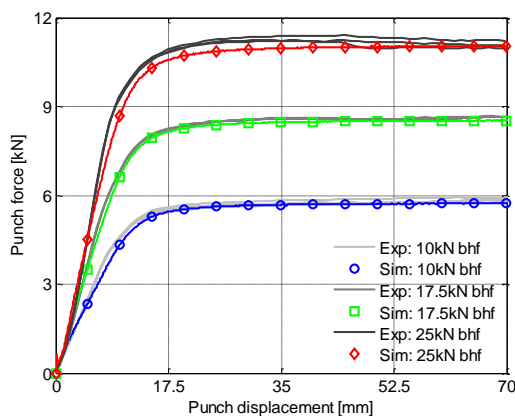


Fig. 6: Experimental and numerical punch force displacement-diagrams for different lubrication conditions

values are observed towards the free edges of the strip (lubricant pressure equals zero) and towards the regions where no contact occurs between the sheet material and the tooling, indicated by the gray areas.

Figure 4-6 shows experimentally obtained punch force-displacement diagrams for different blankholder forces, lubrication amounts and

lubrication types. Mainly boundary lubrication will occur if an amount of 0.6 g/m^2 is used, i.e. there is not enough lubricant available to initiate hydrodynamic effects. In practice, a lubrication amount of 0.6 g/m^2 can be expected in the middle of a coil due to migration of lubricant, even though a larger amount of lubricant was initially applied by the mills. To demonstrate the functioning of the advanced friction model in the boundary lubrication regime, experiments have been conducted using 3 different blankholder forces using a fixed velocity of 20 mm/s (see Figure 4). A lubrication amount of 0.6 g/m^2 Quaker N6130 Prelube was applied to the sheet surfaces before executing the experiments. The experimental punch force evolves to a steady-state value for all experiments, and shows a good repeatability between triplicates. As can be seen, the trend of the experimental punch force–displacement diagrams can be predicted precisely by using the proposed boundary lubrication friction model. The simulation time increases by less than 3% compared to using a Coulomb friction model.

Figure 5 shows a comparison between the experimental results and FE results using the classical Coulomb friction model. The value of the (constant) friction coefficient is set to $\mu = 0.155$ to fit the experimentally obtained punch forces using a blankholder force of 10 kN . It can be observed that the constant value does not result in an accurate prediction of experimental punch forces when the blankholder force is increased. Clearly, to describe the punch force–displacement curves accurately, the friction coefficient should be refitted for each blankholder force using the Coulomb model, whereas a good agreement for all three blankholder forces is obtained using the advanced friction model.

Increasing the amount of lubricant to e.g. 2.0 g/m^2 allows for hydrodynamic effects to occur during drawing. Increasing the lubricant amount, or by using the high viscosity Prelube PLS100T, decreases friction during forming, lowering the punch forces as shown in Figure 6. The decrease in punch force for increasing lubrication amounts indicates that part of the load is carried by the lubricant. Compared to the results shown in Figure 4, an increased velocity of 50 mm/s was used during the experiments to trigger the influence of hydrodynamic effects on the required punch forces. As shown, the trend of the experimental punch force-displacement diagram can be predicted accurately using TriMM if a lubrication amount of 0.6 g/m^2 is used. Increasing the lubrication amount to 2.0 g/m^2 , decreases the required punch force to deform the top hat section, which is also observed from the experiments. The load carrying capacity of the lubricant is overestimated for the Prelube FERROCOAT® N6130, leading to an underestimation of the required punch force. The

reason for this is yet unknown, but for the high viscosity Prelube Fuchs Anticorit PLS100T a good prediction of the punch force-displacement diagram is obtained.

4 CONCLUSIONS

It is shown in this paper that the friction coefficient in sheet metal forming is not constant and depends on the punch stroke, punch speed, blankholder force and location in the product. The presented software solution allows for calculating the local friction behavior during forming, enabling advanced friction modeling in FE forming simulations. The combined experimental and numerical study for the top-hat section shows good agreement for different blank holder pressures, lubrication types and lubrication amounts. Also for varying process settings, the advanced friction model enables an accurate prediction of experimental results. The FE simulations show that the friction coefficient changes per process setting, which contradicts the use of a fixed value for the friction coefficient as is used in the Coulomb friction model. This work demonstrates that advanced friction modeling assists in improving the accuracy of a first process simulation, going towards a ‘first-time-right’ simulation of metal forming processes.

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