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NUMERICAL INVESTIGATION OF EFFECT OF PRESSURE EXPONENT FOR ENHANCED COULOMB FRICTION MODEL

Lucas Alexander de Carvalho
PhD student, University of Miskolc, Institute of Material Science and Technology
3515 Miskolc-Egyetemváros, e-mail: de.carvalho.lucas.alexandre@student.uni-miskolc.hu

Zsolt Lukács
associate professor, University of Miskolc, Institute of Material Science and Technology
3515 Miskolc-Egyetemváros, e-mail: zsolt.lukacs@uni-miskolc.hu

Abstract
The complexity of sheet metal parts has reached a level, that without supporting process planning applications almost impossible to design the process planning. Because technology is sharpened to the limit the slightest disturbance in the production results in a waste product. The lubrication condition used during the sheet metal forming is crucial to the success of production. Therefore, the need to model the resulting tribological system as accurately as possible has become increasingly important. This paper purpose with the physically based measurement of the so-called enhanced Coulomb model material parameter used in AutoForm software and the analysis of its effect.

Keywords: *enhanced Coulomb-model, measurement of pressure exponent, AutoForm, tribology in sheet metal forming*

1. Introduction

Efficient production processes can only be developed using well defined sheet metal forming simulation models. Therefore, to improve the accuracy of FEM (finite element methods) simulations, sophisticated friction models must be introduced. The AutoForm program is one of the most widely used FEM tools for sheet metal forming (SMF) and include a few options for the description of friction. The methods in AutoForm include the traditional coefficient of Coulomb. Although it is sometimes an acceptable approximation when compared to a certain process, it is well known that in reality friction coefficient is not constant in SMF but dependent of process variables such as: anisotropy, temperature, contact pressure and velocity. These friction models are built from physically based models, enabling modelling friction in the mixed lubrication regime (Hol, 2017; Jeswiet et al., 2008; Tisza et al., 2017).

When approaching tribology in SMF it is also relevant to mention the state-of-the-art technology, the virtual tribology (Lacues et al., 2019; Sigvant et al., 2018; Berahmani et al., 2022; Bouzid et al., 2022). Even though the virtual tribology has been proved to be a good solution for the SMF simulation, the enhanced Coulomb models are still an important alternative due to its cost efficiency and accessibility (Gil et al., 2016; Dalton et al., 2001; Huang et al., 2022). In consequence to that, there is the need for engineering efforts towards establishing a process that accurately access the coefficient of friction. The present method discussed in this research is a combination of a physical measurement and the enhanced Coulomb equations. The physical measurement step is very important to fulfil the input parameters for the enhanced Coulomb model equations to result a more reliable description of friction for the SMF simulation. Enhanced Coulomb models in AutoForm account with the influence of velocity and contact pressure to an improved approximation of friction to the real process resulting in the effective coefficient of friction μ_{eff} (Bouzid et al., 2022; Oliveira et al., 2018).

The contact pressure is one of the process parameters that most influence the friction and may be evaluated at both macro and micro scales. In a micro scale the topography of the in-contact surfaces flattens out as the contact pressure rises. In consequence to that there is a change in the geometry of the contact area leading to a change on the coefficient of friction. In a macro scale the contact pressure increases on the flange area as the sheet flows into the cavity of the die. A heterogeneous contact pressure distribution can be detected because the thickness of the sheet may change differently in different locations of the sheet over time (during the flow of the material). Thus, a heterogeneous contact pressure distribution can be found (Gil et al., 2016; Oliveira et al., 2018; Sigvant et al., 2019).

This study aims to investigate the effect of the pressure dependent friction model on shear stress and friction work on the SMF simulation of a prototype part with different Gaussian curves along its edges. As a result of previous studies (Carvalho et al., 2022) the current investigation is focused on the pressure dependent parameter e (pressure exponent) of the pressure dependent enhanced Coulomb model on AutoForm.

The base for enhanced Coulomb models typically involves integrating several key concepts and theories (Coulomb, Hertizan, Stribeck curve, Elastohydrodynamic Lubrication, Shear-thinning behaviour, Viscolity and the surface roughness and texture). In general, Enhanced Coulomb models are based on extending the classical Coulomb friction model resulting on the enhanced coulomb models. By combining these mathematical principles, enhanced Coulomb models provide a more detailed and accurate description of friction and lubrication behaviour under mixed lubrication conditions.

The current study focusses on the pressure dependent enhanced Coulomb model. The effective pressure dependent coefficient of friction (μ_{eff}) is shown in the *Equation (1)*:

$$\mu_{eff} = \mu\left(\frac{p}{p_{ref}}\right)^{(e-1)} \tag{1}$$

Where μ is the friction coefficient of Coulomb model, p the normal pressure, p_{ref} the reference normal pressure, e is the pressure exponent.

2. Physical measurement of pressure exponent parameter

No universal method has yet been established for estimating the coefficient of friction for SMF simulation. The diversity of geometries on the tool-material interface as the complexity of the Gaussian curvatures and the presence of a variety of stress and strain states in different areas and different moments along the sheet metal forming process are the main reasons.

There are several efforts to achieve a reliable method that fulfils the correct description of friction coefficient for the SMF simulation. The friction measurement device created at the Institute of Material Science and Technology at the University of Miskolc is based on the strip drawing and comes from previous studies mentioned both in the literature and in industry cases (Sigvant et al., 2018; Dalton et al., 2001; Gao et al., 2024; Tavares et al., 2021; Kirkhorn et al., 2012; Trzepiecinski et al., 2020; Geng et al., 2012). The measurement device is shown in *Figure 1* and follows a long history of studies in sheet metal forming at our institute (Tisza et al., 2017). More details of the functionality of the device can be found on previous publication (Carvalho et al., 2022).

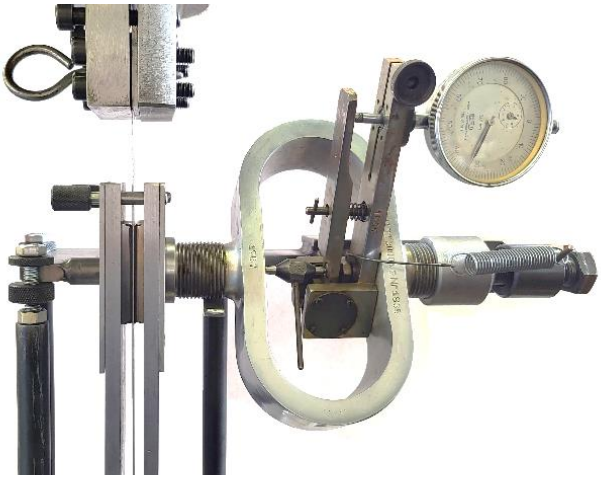

Figure 1. *Friction measurement device developed by Institute of Material Science and Technology*

The physical measurement device was built to be assembled to the MTS Universal Testing Machine which control the pulling force (resistance force). The normal pressure between the tools is defined by a compression dynamometer. The normal force is then calculated considering the contact area between tool and metal strip and the results are applied to Equation 2. The calculation of the friction coefficient (μ) is based on the well-known Amontos-Coulomb friction model. F_T and F_N are the tangential and normal forces, respectively (Carvalho et al., 2022).

$$\mu = \frac{F_T}{2F_N} \tag{2}$$

The *Figure 2* presents the results for the friction coefficient. The interpolation curves and the calculated variables (e and p_{ref}) were based in *Equation 1*. The tests were performed with AISI 304 Stainless Steel sheet metal samples, and heat-treated carbon steel tools and the normal mineral lubricant oil.

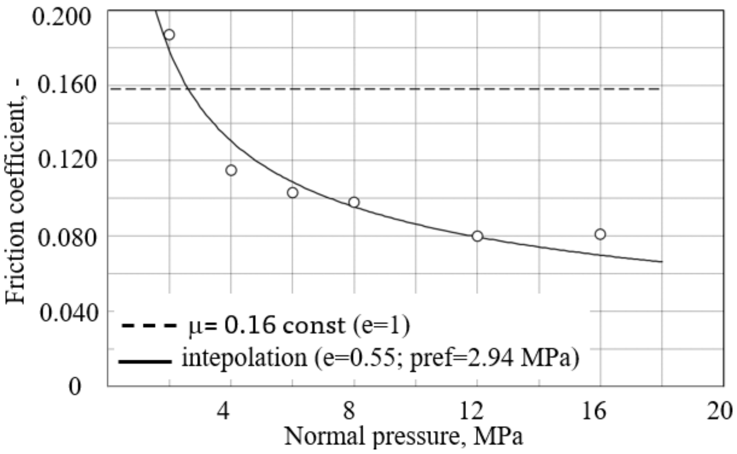

Figure 2. *Friction results and interpolation and the calculated parameters (e and p_{ref})*

3. Numerical investigations of the effect of the pressure exponent

3.1. Investigated tool geometry

The Gaussian curvature is an important concept in sheet metal forming design for describing how a surface curves into two orthogonal directions. It is a critical concept to understand and predict how the sheet metal will behave when formed into complex shapes. A complex design will influence the material behaviour and in consequence have an impact in friction. (Kubli, 1996). Understanding this concept helps creating high-quality and defect-free formed metal parts. To evaluate different critical aspect of SMF the tool designed for the current study is presented on *Figure 3*.

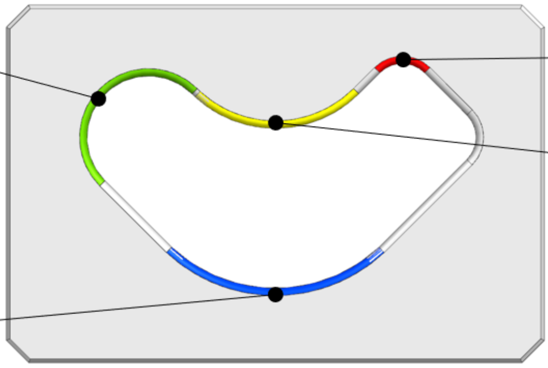

Figure 3. *Die entry line regions and location of investigated points*

On *Figure 3* it is indicated 4 different evaluated regions including 3 concave curves (regions: A, B, and D) and one convex curve (region C). The Gaussian curvature is the multiplication of the major and minor curvatures. The major curvature is constant (convex value) due to the constant rounding radius of the die entry line (R_{die} = 5mm). For the minor curvatures the regions A, B and D present a concave curvature (negative minor curvature), where region A has the largest curvature and region D has the smallest minor curvature. For the section in region C booth major and minor curvatures are convex, resulting in a positive Gaussian curvature (Kubli, 1996). The points I., II., III. and IV. are the center points of each region. The details of the analyzed regions and the investigated points are described in the *Table 1*.

Table 1. *Geometrical parameters of the investigated regions and their points*

Regions Points	Radius mm	*Degree* °	Major curvature 1/mm	Minor curvature 1/mm	Gaussian curvature 1/mm^2
A	20	90	–	–	–
I.	–	–	0.201	–0.023	–4.63 10^{-3}
B	40	180	–	–	–
II.	–	–	0.201	–0.015	–3.083 10^{-3}
C	100	90	–	–	–
III.	–	–	0.201	9.558 10^{-3}	1.908 10^{-3}
D	80	90	–	–	–
IV.	–	–	0.201	–7.235 10^{-3}	–1.450 10^{-3}

3.2. Numerical simulation

The application of the pressure dependent enhanced coulomb model on AutoForm was made for the simulation of the geometry introduced in *Figure 3* and *Table 1*. The analysis was made a single action draw operation of the blank also indicated die concept on the right side of *Figure 4*. The final workpiece geometry is shown on the left side of *Figure 4*. On the right side of *Figure 4* show in detail the positions of tool elements in the open position of the die: the die, the binder (blank holder) and the punch.

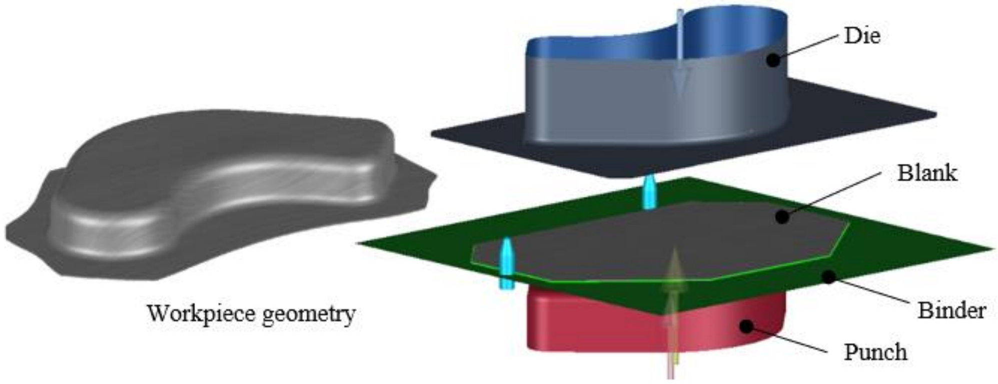

Figure 4. *Workpiece geometry (left) and the single action draw die concept (right)*

The designed blank is a rectangular shape with different chamfered corners. The depth of the drawing operation was 30 mm. The blank material is an austenitic corrosion resistant steel plate (AISI 304 Stainless Steel sheet) with 1 mm of thickness. An elastic and non-linear isotopic hardening material model was used for the material characterization. The Swift hardening curve formula is described in *Equation 3*

$$\sigma = C(\varepsilon_0 + \varepsilon)^n \tag{3}$$

Where σ is the true stress, C the strength coefficient, ε_0 the initial plastic strain, ε is the plastic strain and n the strain hardening exponent. The parameter values are shown on *Table 2*.

Table 2. *Material parameters input for hardening curve*

C(MPa)	ε_0 (–)	*n* (–)
1637	0.05	0.53

The drawing simulation investigated the two friction states presented in *Figure 2*. For the simulation model it was first considered the general Coulomb model with the pressure exponent parameter (e = 1) and in sequence the pressure dependent Coulomb model (e = 0.55).

4. Results and discussion

The results for the effect of the two pressure exponents (e = 1 and e = 0.55) are presented in *Figure 5*. The effect of e was evaluated trough 3 output variables: the maximum shear stress (a), the friction work (b), and the friction shear stress (c).

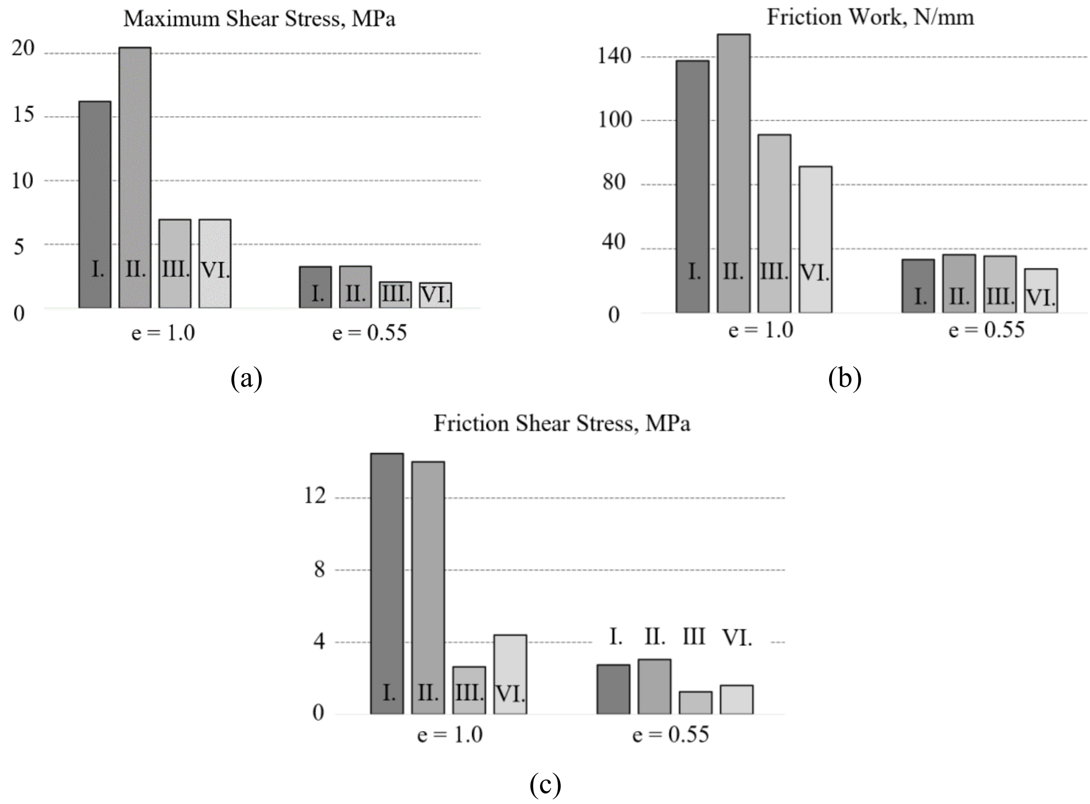

Figure 5. *Effect of the pressure exponent for the different result variable: a) Maximum shear stress; b) Friction work; c) Friction shear stress in the investigated points*

For the three analyzed process result variables the constant friction model (e = 1) has shown a larger range, fact that can be associated to the differences in the curvature of the individual regions. The higher values were found for the smaller radius (point I. and II.). Although the region B (point II.) has a larger radius compared to region A (point I.), the result variables indicate a similar magnitude. This fact can be associated to the bigger angle of the curve on region B (180°). The pressure dependent friction (e = 0.55) has shown lower results for the listed outputs when compared to the constant friction model (e = 1). When comparing the range of the results of e = 0.55 in the different chosen regions the enhanced model has a smaller influence on the process but a similar tendency when compared to e = 1.

Figure 6 presents the distribution of the friction coefficient on the workpiece with expected higher friction coefficient on the flange region. The wide range of values (0.15–0.05) reinforce the previously discussed and adds towards the discussion regarding the proportionality between shear and normal forces described in the friction coefficient. The high range of effective friction coefficient values indicate a high influence of the pressure exponent to the friction distribution and its importance for SMF simulation.

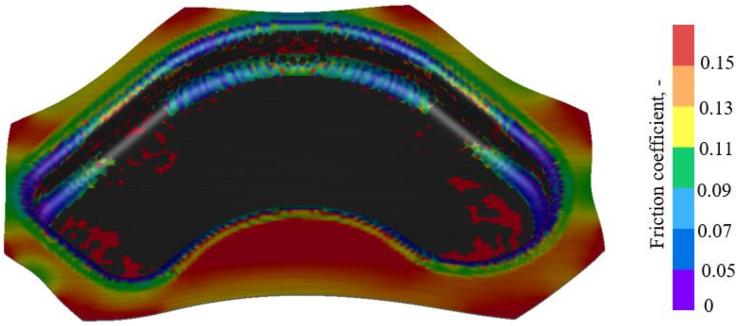

Figure 6. *Distribution of the friction coefficient on the punch side surface*

5. Conclusion

The findings of this investigation support the effectiveness of the physical measurement device combined with enhanced Coulomb models as a useful tool for SMF process optimization. In the present study, higher values of maximum shear stress were found for points I. and II. for (e = 1). Therefore, the maximum shear stress results indicates that the constant friction model describes a process with a higher chance for material failure on regions A and B due to the increased maximum shear stress at these locations, affecting the wear of dies. The friction shear stress results have shown that the enhanced Coulomb model (e = 0.55) relates to a process were less chances of tool wear and better part quality are expected. A similar behavior is also expected for regions III. and IV. for the constant Coulomb model (e = 1) but a significantly higher stress was found for regions I. and II. for (e = 1). Regarding the friction work higher energy dissipation is expected for the constant Coulomb model, that may result in higher heat generation and increased toll wear.

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