ABOUT THE STATIC COEFFICIENT OF FRICTION UNDER SHEET METAL FORMING CONTACT CONDITIONS

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SUMMARY
In a sheet metal working process, products or half products are manufactured from a flat sheet of metal. The friction between the material and the tools influences the process by modifying the strain distribution. From a numerical point of view, a constant Coulomb coefficient is commonly used in FEM simulations to model the frictional behaviour of contacting solids. However, this coefficient varies in time and space with many parameters. We present here a new control of the flat die test friction device which allows the determination of the static coefficient of friction. Experimental results are given for hot dipped galvanised steel sheets. We also propose a local friction law based partly on experimental results. FEM simulations are carried out for an axisymmetric stamping operation using the defined friction law. We compare the computed sheet thickness related to a local or global coefficient of friction. A localised influence of the local model is found on the punch nose that underlines the higher friction coefficient in this zone.

Keywords: friction law, static friction, press forming, simulation

1 INTRODUCTION
Regarding to the stamping process, the interest of the determination of the static coefficient of friction is double. Firstly, it defines the friction conditions under which the sheet begins to slide along the die. Secondly, it provides perhaps a better estimation of the friction coefficient on the punch where the sliding lengths are very small.

It is well known that the static coefficient of friction is generally larger than the dynamic one when a tangential force is applied to a slider. Dynamic friction has been deeply investigated in the case of various tool / steel-sheet interfaces [1][3]. The influence of static friction seems not to be negligible on the result of a drawn steel part. In order to be able to evaluate such an influence, the following points have to be considered:

- The experimental determination of the static coefficient of friction for various tools / lubricant / sheet. Results are shown for lubricated and not lubricated hot-dipped galvanised steel strips (0.77 mm, Ra = 1.8µm) widely used in the automotive industry with a contacting pressure in the range of 1 to 30 MPa.
- The influence of a local friction on the results of FEM calculations. The friction law must take into account the higher values of friction coefficient for small sliding lengths. The presented friction law allows to investigate the influence of a sliding length dependent friction coefficient on the results of an academic stamping part. Differences in terms of thickness distribution between the local and global friction laws are given. They underline the localised influence of the friction law on numerical calculations.

2 EXPERIMENTAL DETERMINATION OF THE STATIC COEFFICIENT OF FRICTION
2.1 The friction device
In order to help the understanding of the friction phenomena and to find relevant models for numerical simulations, we need to characterise the friction that occurs at the sheet/tools interface. A strip draw test between flat dies (see Fig. 1) allows to characterise a value of the Coulomb coefficient in the blank holder area under pre-defined lubrication and pressure conditions.

An advantage of this flat dies apparatus is that there is generally no macroscopic plastic strain of the steel strip so it allows to accurately measure the Coulomb friction’s coefficients µ (with µ = F/2H).
Traditionally, the result of this flat dies test is a dynamic Coulomb friction’s coefficient. It has been shown that the speed control of the strip does not allow to characterise accurately the beginning of sliding: i.e. the static friction of contacting materials.

A new control of the strip is added to this apparatus in order to determine the static coefficient of friction. A gradual increase of the tangential load $F$ tends to break the adhesion at the sheet-tool interface. A sudden decrease of the tensile load is produced by the initial sliding of the strip (see Fig. 2). The principle is adapted from the slide angle tester where the increase of the tangential force is related to an increase of the angle of inclination of the tester [2].

2.2 Experimental procedure

The control of every test parameter is very important to insure a good reproducibility of tests.

2.2.1 Preparation of strip

Strips of length 500 mm are taken from a 900 $\times$ 1000 $\times$ 0.8 mm$^3$ steel sheet in the rolling direction. Cutting burr is removed from the sample. The strip is cleaned with hexane before applying Quaker Ferrocoat N 6130 when lubrication is needed. An experimental procedure has been chosen that allows to apply a controlled quantity of lubricant of 1.5 g/m$^2$/face for these experiments. In this range of lubricant quantity, no influence of squeeze film can be detected.

2.2.2 Preparation of tools

The apparent contact length is 15 mm in the sliding direction (apparent contact surface depends on the strip width). Tool material is either steel Z160CDV12 or cast iron FGL240T7, commonly used as tooling materials for deep drawing operations.

Notice that a precise tool grinding is performed perpendicularly to the sliding direction in order to insure a good homogeneity of contact pressure. The contacting surface is polished with glass-paper (1200-grade, $R_a = 0.06$ µm) perpendicularly to the sliding direction and cleaned with hexane after each test. Rotation axes of the left tool is locked during experiments [1][3].

2.2.3 Tests conditions

Table 1 summarises the test conditions.

<table>
<thead>
<tr>
<th>Contact pressure (MPa)</th>
<th>Strip Width (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 to 8</td>
<td>50</td>
</tr>
<tr>
<td>10</td>
<td>40</td>
</tr>
<tr>
<td>15</td>
<td>25</td>
</tr>
<tr>
<td>30</td>
<td>15 (2 strips)</td>
</tr>
</tbody>
</table>

Table 1. Test conditions

2.3 Results

2.3.1 Influence of lubrication

Fig. 5 presents the influence of the sheet lubrication on the value of the static coefficient of friction for Z160CDV12 tool material. Results show a big influence of lubrication on the result of static coefficient of friction. For dry friction, macroscopic plastic strain appears on the strip for contact pressures higher than 10 MPa. Fig. 5 shows that the strip plasticity appears in case of dry contact conditions where galling occurs and increases significantly the critical shear stress value.

2.3.2 Influence of tool material

In this paragraph, we will focus on static coefficients of friction to be implemented in the numerical simulation. These coefficients are determined in case of two tool materials (automotive parts lubrication conditions).

Fig. 6 presents the influence of steel Z160CDV12 and cast iron FGL240T7 tool materials on the static coefficient of friction.

We also represent the evolution of friction coefficient depending on the quality of cleaning with hexane. This cleaning seems to be very influent on the value of this coefficient of friction (from 0.2 to 0.5 at 2 MPa) so that the results relative to the dry contact have to be taken with caution.

These results underline the determinant effect of the lubricant on the static friction coefficient, particularly in this case of boundary lubrication.

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coefficient of friction. We observe a slight decrease of the friction coefficient with an increasing contact pressure for both materials. It varies from 0.225 down to 0.195 in a range of contact pressure from 1 to 30 MPa. The two materials seem to have a very similar variation of the static coefficient of friction depending on contact pressure.

2.3.3 Comparison with dynamic results

This apparatus allows either dynamic or static determination of the coefficient of friction. Static coefficient of friction results are compared to dynamic one for 1 MPa apparent contact pressure and Z160CDV12 tool material. The sliding speed is 10 mm/s. The average dynamic coefficient of friction is 0.16 on our apparatus. These results are in good agreement with DEVINE [1]. Our conclusion is that the difference between static and dynamic results is far from negligible (0.06 at 1MPa) and could influence the forming process.

2.4 Conclusion on experimental results

Some conclusions can be drawn from our observation of the static coefficient of friction in drawing contact conditions.

First of all, this new control of the strip draw test between flat dies seems to give fairly reproducible results. It allows also to characterise a value of the static coefficient of friction for extreme contact conditions : dry contact with galling for example.

Secondly, it highlights the fact that the influence of tool material is not significant on the value of the static coefficient of friction. However, the results present a marked difference between the static values and the dynamic ones.

Finally, this test presents an interesting point of view on the friction that occurs during the deep drawing operation, especially for the transition from static to dynamic contact. It also offers some perspectives for friction models to be applied in numerical simulation of sheet material forming.

3 INFLUENCE OF A LOCAL FRICTION LAW ON FEM CALCULATION RESULTS

3.1 Introduction

Friction is a very influential parameter of the deep drawing process, especially when the surface/thickness ratio of the blank is large. In a deep drawing operation, sheet stretching occurs first in the punch nose area. For a certain punch displacement, the material is then drawn into the die by the punch [1].

This transition from a quasi-static to a dynamic frictional behaviour in the blank holder area depends on two main parameters : the equivalent stress state of the blank and its frictional behaviour against the tools. The higher the friction is, the later the part is drawn into the die. This example simply highlights the effect of a different static coefficient of friction on the result of a drawn part. In this case, the value of the static friction coefficient could influence the thickness distribution along the part.

Other effects can be found on the punch were the sliding lengths are small. In case of an hemispheric axisymmetric deep drawing operation, traditional constant Coulomb friction’s coefficients are unable to predict accurately the position of minimal thickness zone (a circle in this case) [1]. However, the use of a local (time and space dependent) friction coefficient can provide a better agreement between experiments and results of numerical simulations.

3.2 Numerical model

The implementation in FORGE2® of the local friction model is summarised below.

3.2.1 Mechanical equations

The equilibrium equation is written as follows :

$$\text{div}(s) = \rho \gamma + \text{grad}(p)$$

where $s$ is the deviatoric part of the stress tensor, $\rho$ the density, $\gamma$ the acceleration and $p$ the hydrostatic pressure. In this case, $\rho$, $\gamma$ and body forces are neglected.

The plastic incompressibility is computed as $\text{div}(\nu) = 0$ where $\nu$ is the two component velocity field : $V_r$ and $V_z$.

The 2D finite element discretisation is based on a mini-triangular element velocity and pressure linear. A bubble function is added to the velocity field at the centre of element (P1+/P1 element). Notice also that no remeshing is used for these simulations.

The discretisation of the equilibrium equations leads to a non linear equation system solved by a Newton-Raphson iterative method.

Calculation is performed using penalised contact formulation between the sheet material and the tools so that the friction effects are computed with much care.
3.2.2 Geometry and cinematic

Fig. 5 gives a representation of the axisymmetric geometry of the hemispheric punch forming operation. Dimensions are as follow:

- Punch diameter : 125 mm
- Die and blank holder
  - Die radius : 10 mm
  - Internal diameter : 128.15 mm
  - External diameter : 270 mm

The blank diameter is equal to 240 mm with a 0.8 mm thickness. Two layers of linear triangular elements are used for the space discretisation of the blank and the contacting surface of the elastic tools.

![Fig. 5: Presentation of the geometry, the meshing and the process boundary conditions](image)

3.2.3 Material rheology

In this case, the blank is assumed isotropic. Rheology is elasto-plastic. The constitutive law of the steel material is calculated with respect to:

$$\bar{\varepsilon} = 2K_0 (\bar{\varepsilon} + \bar{\varepsilon}_0)^n (\sqrt{3} \bar{\varepsilon})^{m-1} \bar{\varepsilon}$$

with $K_0 = 310$ MPa, $n = 0.22$, $m = 0.01$ and $\bar{\varepsilon}_0 = 0.00678$

Elastic parameters for both elastic tools and blank are the Young modulus ($E = 210$ GPa) and the Poisson ratio ($\nu = 0.3$).

3.2.4 Frictional stress formulation

In case of FORGE2® calculations, regularised formulation of Coulomb friction is used so that the friction contribution is:

$$\tau = \mu \sigma_n \left( \frac{1}{\sqrt{\Delta Vg^2 + \Delta Vg_0^2}} + K \right) \Delta Vg$$

With $\mu$ the local Coulomb friction’s coefficient, $\sigma_n$ the local contact pressure, $\Delta Vg$ the sliding speed, $\Delta Vg_0$ and $K$ the two regularisation parameters.

3.2.5 Local friction model

In order to take into account the effects of static friction using such a regularised tangential stress formulation, the following local friction law is implemented in FORGE2® calculations. This simple law depends on four parameters: $\mu_s$ and $\mu_d$ the static and dynamic coefficients of friction; $l_1$ and $l_2$ that allow to control the transition from a static to a dynamic frictional behaviour.

$$\mu = \frac{1}{2} \left[ (\mu_d + \mu_s) + (\mu_d - \mu_s) \tan \left( \frac{l_1 - l_2}{l_2} \right) \right]$$

Figure 6 represents the two different laws used in the numerical simulations. In our numerical simulations, the blank holder force represents an initial contact pressure in the blank holder area of 1.14 MPa. For that reason, the static coefficient of friction will vary in the range of 0.20 to 0.25 in the numerical simulation to be presented below (see paragraph 3.2.2).

![Fig. 6: Presentation of the implemented friction laws](image)

3.3 Results and discussion

3.3.1 Variables to be observed

Variables to be observed have to be chosen with much care. They have to underline possible effects due to the global or local friction formulation.

Historically, the punch force and the thickness distribution are the most used variables to be observed in case of tribological problems. They both take into account the frictional and rheological phenomena. Our purpose is to find a variable that doesn’t rely too much on rheology but rather on friction. That is not really the case of the punch force variable. However, a good accordance on this point is found with the thickness distribution. Moreover, this variable is a local one, resulting of the cumulative effects of frictional phenomena during the forming operation.

As we try to observe the effects of the transition from a quasi-static to a dynamic frictional behaviour at the tool/sheet interface, we introduce here a new variable that we call the “feeding start” variable. The result gives the punch position for a very small displacement of the blank in the blank holder area. In a certain way, it characterises the transition from a stretching to a drawing strain mode.

Results concerning these two variables (thickness distribution and feeding start variable) are presented below.
3.3.2 The feeding start variable

Fig. 7 presents the result of simulation concerning the “feeding start” variable for two blank holder forces of 32 kN and 160 kN and two critical blank displacements of 0.05 mm and 0.1 mm (notice that for these simulations, we use a regularised Coulomb friction law that allows a small sliding for $\tau < \mu \sigma_n$).

![Fig. 7: Punch displacement at feeding start versus friction coefficient](image)

These numerical results show a clear linear variation of the feeding start variable with an increasing coefficient of friction. Up to this punch displacement, the blank is mainly submitted to a stretching strain mode.

We observe the great influence of the blank holder force on the start of material feeding in the blank holder area. Up to the beginning of sliding, quasi-static contact condition can be assumed in this zone.

Results show the influence of our local friction law on this variable by increasing the punch displacement before a significant sliding of the flange (see Fig. 7). This modification of transition time from expansion to drawing strain mode could influence the final part thickness distribution. However, as one can remember, the final feeding of material decreases with an increasing blank holder force for a given friction value.

3.3.3 Influence on thickness distribution

Figure 8 presents the thickness distribution (punch area) on deformed configuration for a displacement of 62.5 mm of the punch. Simulations have been performed for both constant (0, 0.13, 0.20) and local friction laws.

Classical variations of thickness distribution are found for simulation using a constant coefficient of friction:

- Increasing thickness on the punch nose for an increasing friction.
- Displacement of the minimal thickness position on the punch for an increasing friction (when zero friction is assumed, minimal thickness is found at the pole).

We do not observe a significant difference between the local and constant 0.13 distribution in the blank holder area. Same variations are found for the second local law with a higher static coefficient.

Concerning the feeding of material in the blank holder area, no influence is found in comparison with the constant 0.13 friction formulation (see paragraph 3.3.2). So, a localised influence of this local formulation of friction is found in the punch area that tends to modify the thickness distribution and moreover the minimal thickness position.

4 CONCLUSION

Experimental and numerical results in relation with friction during the stamping process were presented in this paper. Experimental static Coulomb friction values were given for hot dipped galvanised steel. We also proposed a local friction law based on experimental results to be used in numerical simulations. FEM calculations show a localised influence of this friction law on the blank thickness distribution: increased pole thickness and displacement of minimum thickness position in comparison with constant Coulomb coefficient simulations. We plan to use of a pressure, speed and sliding length dependent analytical model for local friction definition, which could offer a more physical and complete description of frictional phenomena in deep drawing simulations.

5 REFERENCES