FRICTION MODELLING IN SHEET METAL FORMING SIMULATIONS: APPLICATION AND VALIDATION ON AN U-BEND PRODUCT

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ABSTRACT: The accuracy of sheet metal forming simulations strongly depends on, amongst others, friction modelling. The industrial standard is to use the Coulomb friction model with a constant coefficient of friction. However, it is known that the true friction conditions are dependent on the tribology system, i.e. the applied sheet material, coating and tooling material, the lubrication and process conditions. In this paper, an approach is presented for friction modelling in sheet metal forming simulations. The approach is applied to the forming of U-bend test parts for varying tribology systems as commonly used in the automotive industry. The friction conditions per system are described using a physically-based friction model included in the Triboform Software. Friction in the U-bend simulations are described as a function of local contact pressure, relative sliding velocity and straining in the sheet material. The simulation results are validated using U-bend forming experiments. It is concluded that the numerical prediction of the punch force magnitude is highly sensitive to friction. In addition to an overall improvement of the prediction accuracy of stamping simulations by including friction modelling, this approach enables to model friction and the effect of varying tribology systems on the final stamped part quality.

KEYWORDS: Sheet metal forming, friction modelling, FE simulations, experimental validation

1 INTRODUCTION

There are two physical phenomena that have a profound influence on the accuracy of simulation results in sheet metal forming, namely the sheet materials plastic properties and the frictional behaviour of the applied tribology system. During the last decade, large improvements have been made in the field of constitutive modelling of sheet metals [1], but still a Coulomb friction model with a constant coefficient of friction is used in the majority of sheet metal forming simulations.

There is a general demand in the automotive industry to reduce both lead time and development cost, which can be achieved by increasing the usage of Finite Element (FE) simulations. However, this requires an accurate description of all physical phenomena including friction in metal forming simulations in order to achieve the required savings. At the Stamping CAE & Die Development Department at Volvo Car Group, it is concluded that advanced friction modelling is the way forward for improving metal forming simulation accuracy. For this purpose, an Advanced Engineering project was started of which a selection of the project results are presented in this paper.

From an initial numerical study performed in the project, it was concluded that the relative velocity between the sheet and the tooling has a major influence on the simulation results. In a servo press or mechanical press, as used for the U-bend tests, the relative velocity can be quite high and therefore it is important to include this effect in sheet metal forming simulations. Figure 1 shows experimentally measured punch force resulting from a U-bend test together with simulation results using varying empirical friction models. The numerical results demonstrate that the only way to model the increase of the punch force at the end of the stroke is to include a dependency of the frictional behaviour on relative velocity. The results in Figure 1 also demonstrate that in order to model the overall shape of the experimentally measured punch force-displacement curve, a combined pressure and velocity dependent friction model is required. Finally, a good agreement between experiments and simulations was achieved by tuning a user friction model for this specific tribology system.

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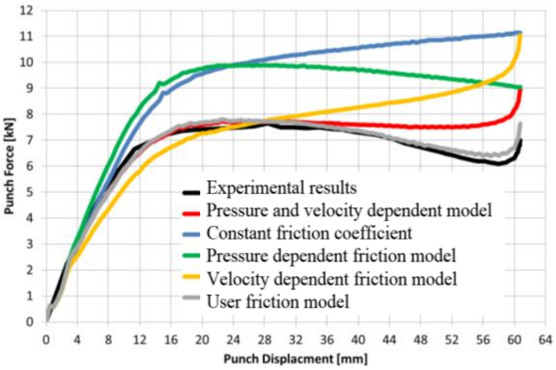

Fig. 1 *Experimental Punch Force curve for a U-bend test together with numerical results for varying empirical friction models.*

However, further work in the project revealed that for a slight modification of the tribology system by e.g. changing the lubrication amount or sheet material type, the selected parameters of the empirical friction model were no longer valid, i.e. empirical friction models are not generally applicable and able to accurately describe the experimental results for varying tribology systems. Now in order to get an accurate description of the frictional behaviour per system, one must experimentally test and analyse an enormous number of tribology systems that are being used in the automotive industry. This contradicts with the requirement to decrease lead-time and development costs by increasing the use of simulations. Therefore a long-term strategic solution was sought by Volvo Car Group for advanced friction modelling in sheet metal forming simulations.

For this purpose, the Triboform Software is being utilized which is a physically-based friction modelling software provided by Triboform Engineering. The goal of this project was to apply the model for varying tribology systems and create a thorough understanding of the frictional behaviour in U-bend forming. Based on the initial results presented in Figure 1, special attention was paid to the applicability of the friction model for varying relative velocities that can occur in mechanical and servo presses.

2 TRIBOFORM SOFTWARE

Tribological conditions in metal forming processes are dependent on local process and lubrication conditions, loading and local strain state of the sheet material as demonstrated in [2, 3]. The Triboform software allows for multi-scale modelling of a time and locally varying friction coefficient under a wide range of process conditions. The resulting friction model is suitable for subsequent use in commercial FE software, see Figure 2.

2.1 MODELLING APPROACH

The physically-based models included in Triboform enable friction modelling in the mixed lubrication regime. This is achieved by coupling a boundary lubrication friction model [4] and a hydrodynamic friction model [5]. As a user input, information of the tribology system is required, i.e. the applied sheet material, coating and tooling material, lubrication type, lubrication amount and process conditions. This information can either be inputted by the user or extracted from a database, as further described in Chapter 3.

2.2 FRICTION MODEL

Using the Triboform software, a friction model can be created per lubrication system. The resulting friction model describes the frictional behaviour as a function of the:

- local contact pressure;
- relative sliding velocity;
- plastic strain in the sheet material;
- and interface temperature (not included in this study).

The Triboform software also enables the calculation of friction coefficients for process conditions which cannot be evaluated using friction experiments, e.g. for significant straining of the sheet material or high pressures. The latter is especially important for correctly determining and modelling the frictional behaviour in draw beads and die radii. Moreover, since the software makes use of the real measured 3D surface topographies of the tooling and sheet material, also anisotropic friction, regional dependent friction and the products surface quality after forming can be predicted.

2.3 INTEGRATION IN FE SIMULATIONS

A coupling is made with commercial FE packages by implementing the friction model through a user friction subroutine. This enables advanced friction modelling in sheet metal forming simulations with minimal increase of the computation time. In this work, the friction model is implemented in AutoForm^{plus} R5.2 in corporation with AutoForm Engineering.

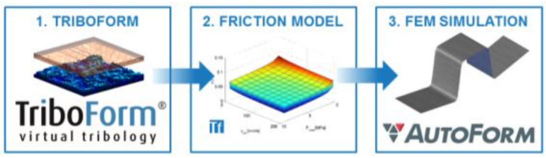

Fig. 2 *Friction modelling approach.*

3 U-BEND FORMING

An impression of the considered U-bend test part is shown in Figure 3.

3.1 TRIBOLOGY SYSTEMS

The results of three tribology systems are presented in this work for the U-bend forming process as specified in Table 1. The lubricants are delivered by Fuchs Schmierstoffe GmbH.

Fig. 3 *U-bend test part of AA6016 sheet material*

Table 1: *Tested tribology systems*

Sheet Material	Thickness [mm]	Lubricant type	Amount [g/m^2]
DX56D+Z	0.7	PLS100T	1.0
DX56D+Z	0.7	PLS100T	2.0
AA6016	1.0	PL39SX	1.0

3.2 U-BEND EXPERIMENTS

The U-bend experiments are performed in a mechanical press at the Industrial Development Center (IDC) in Olofström, Sweden. The ram speed in the beginning of the experiment is approximately 250 mm/s and the maximum relative sliding velocity between sheet and die is close to 200 mm/s.

The die is a single action die and the geometry is based on the Numisheet 93 2-D Draw benchmark. The punch and the blankholder is made of 1.2358 material and is fully hardened, the blankholder is made by grey iron with additional alloys. The gap between the punch and the die is 4 mm.

The blank size is 50 mm x 500 mm and the longest side of the blank is perpendicular to the rolling direction. The blankholder force is generated with four gas springs and can be varied between test series. For the experimental results presented in this work, the blank is only restrained by the blank holder pressure.

Preceding the tests, all steel blanks were cleaned after which the correct amount of lubricant was applied. The aluminium blanks were used and lubricated as received.

3.3 MATERIAL AND LUBRICANT DATA

The material testing of the two sheet materials was also performed at IDC. The results from these material tests were analysed and processed by Volvo Cars and data for the BBC2005 material model was determined for the two sheet materials according to the methodology as described in Banabic et.al [1].

A temperature dependent relation for the viscosity of both lubricants is implemented in the Triboform software provided by Fuchs Schmierstoffe GmbH.

3.4 AUTOFORM SIMULATION MODEL

The U-bend forming process was simulated with AutoForm^{plus} R5.2. A blank holder force - displacement relation was included identical to the experimental relation. The blank holder force was applied in four columns positioned whereby gas springs are located in the die. The BBC2005 material model was used for all simulations and both materials. The ram speed in the simulation was taken identical to the ram speed of the mechanical press, i.e. a sinus shaped curve starting at 250 mm/s and ending at 0 mm/s.

3.5 SHEET AND DIE SURFACE MEASUREMENTS

As an input for the friction calculations, the real 3D surface topographies of the sheet and die surfaces are required. This information can be inputted by the user or extracted from a database.

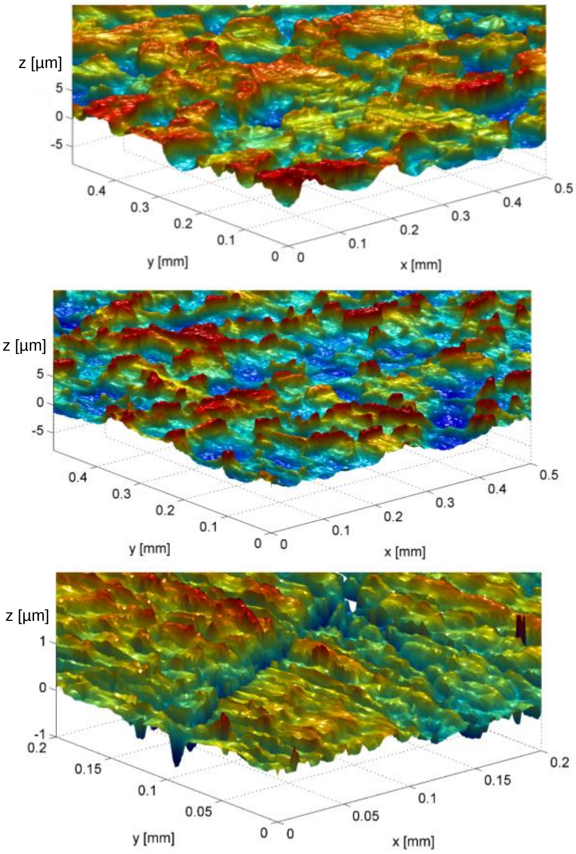

Fig. 4 *Sheet surface topography of DX56D+Z (top), AA6016 (middle) and the U-bend die surface (bottom)*

In this work, the virgin sheet surface topographies have been measured by 3D confocal microscopy at three different locations per material. These measurements have been performed by Tata Steel in IJmuiden, the Netherlands. For both the DX56D+Z and AA6016 material, a single representative measurement was taken and used in the Triboform software for the friction calculations. An impres-

sion of a partial surface topography measurement of the DX56D+Z and AA6016 sheet material is shown in the top and middle image respectively of Figure 4.
The die surfaces have been measured by IDC at eight different locations. Epoxy replicas of the die surfaces were taken and subsequently measured by 3D confocal microscopy. A single representative die surface measurement was taken and used in the Triboform software for the friction calculations. See the bottom image in Figure 4.

3.6 CALIBRATION TESTS

Finally, tribology tests have been performed for the considered tribology systems in Table 1 based on which the Triboform software is calibrated. For this purpose, sliding tests have been executed to determine the interfacial shear strength at the sheet – lubricant – die interface. The resulting shear strength relation is included in the Triboform software and describes the chemical interaction between mating surfaces and the lubricant at the interface. In addition, calibration tests were performed whereby the sheet surfaces have been loaded and subsequently measured by 3D confocal microscopy at three different occasions: as received, after normal loading and after normal loading and sliding. The resulting relation of the real area of contact of the sheet surface topography for varying loading conditions is inputted in the Triboform software.

4 RESULTS

4.1 FRICTION MODELLING

Figures 5 and 6 show the projections of the measured U-bend die surface topography and the DX56D+Z and AA6016 sheet surface topography respectively in the Triboform software. These are the basis simulation models used for the friction calculations for the specific tribology systems. The friction conditions are calculated by loading and sliding the die surface over the sheet surface for a pre-defined amount of lubricant and ranges of process conditions, i.e. contact pressure, relative sliding velocity and plastic strain in the sheet material. The calculation times of the friction analyses range between 10 and 20 minutes on a standard quad-core desktop computer.

4.2 RESULTING FRICTION MODELS

Figures 7 to 9 display the resulting friction models per lubrication systems as given in Table 1. Each friction surface is valid for a certain plastic strain in the sheet material. As the plastic strain increases from 0 to 0.1, with an interval of 0.02, the friction coefficient decreases.

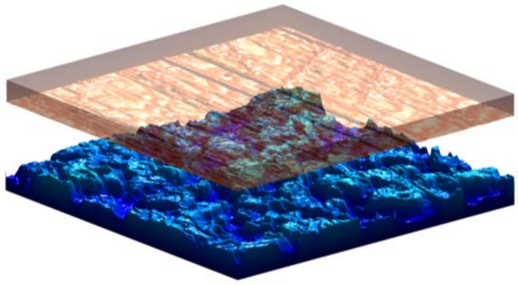

Fig. 5 *Projection of the measured U-bend die surface topography (top) and DX56D+Z sheet surface topography (bottom).*

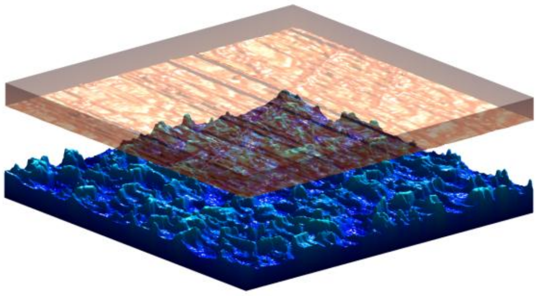

Fig. 6 *Projection of the measured U-bend die surface topography (top) and AA6016 sheet surface topography (bottom).*

The friction models show that all systems have a dependency on both contact pressure, relative velocity and plastic strain in the sheet material. Note however that the slope or magnitude of the dependencies of the frictional behaviour on these parameters differ per tribology system. An increase of the lubrication amount will not only reduce the friction coefficient, it will also reduce the dependency of contact pressure, relative velocity and plastic strain, see Figures 7 and 8. This can be explained by an increase in carrying capacity of the lubricant for an increasing lubrication amount. For the AA6016 tribology system, an overall higher friction coefficient and stronger pressure dependency is observed than the friction models for DX56D+Z sheet material, see Figure 9.

4.3 FORMING SIMULATIONS AND EXPERIMENTAL VALIDATION

U-bend forming simulations are performed whereby only the description of the friction conditions are changed. Simulations are performed using the friction models as presented in Section 4.2 and the Coulomb friction model. Regarding the latter, sheet metal forming simulations are generally performed at Volvo Car Group using a value for the coefficient of friction of 0.15 for steel sheet and a value of 0.12 for aluminium sheet. Therefore, these values are taken as a reference.

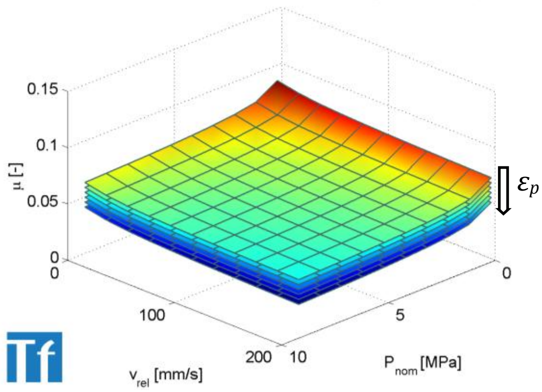

Fig. 7 *Friction model for DX56D+Z with 1.0 g/m² PLS100T lubricant*

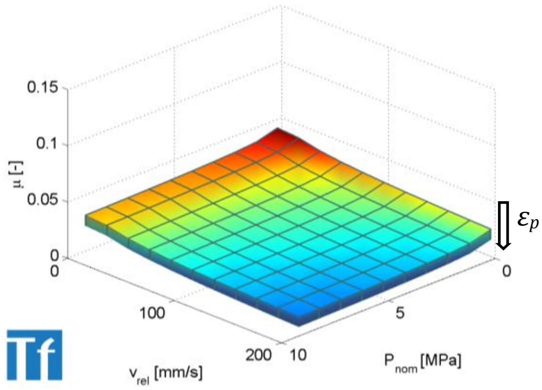

Fig. 8 *Friction model for DX56D+Z with 2.0 g/m² PLS100T lubricant*

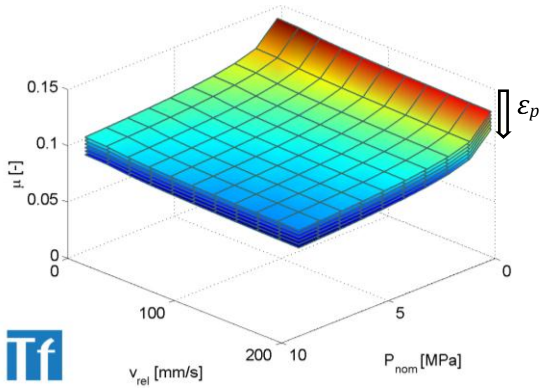

Fig. 9 *Friction model for AA6016 with 1.0 g/m² PL39SX lubricant*

The experimental and simulation results for the U-bend punch forces as a function of the punch stroke are presented in Figures 10 to 12. The experiments are performed in triplicates. The black solid line represents an average result of the experimental repetitions. The vertical bars indicate the variation of the experimental results in terms of one standard deviation, demonstrating a good repeatability of the experimental results. A strong decrease of the punch force is observed for DX56D by increasing the lubrication amount from 1.0 g/m² to 2.0 g/m². This demonstrates the strong influence of tribological conditions present in the process on the frictional behaviour and resulting punch force.

Generally, the agreement between experimental and simulations results including the Triboform friction models are very good. Looking at the results for DX56D+Z in Figures 10 and 11, it is demonstrated that a Coulomb coefficient of friction μ = 0.15 is much too high. This single value can also not represent the two situations of using 1.0 g/m² or 2.0 g/m² PLS100T lubricant. For both cases, the improvement in simulation accuracy when using the Triboform friction models is significant.

For the AA6016 sheet material with 1 g/m² PL39SX lubricant in Figure 12, a Coulomb coefficient of friction μ = 0.12 gives a reasonable prediction of the punch force. Still, using the friction model improves the simulation accuracy, especially for the low blank holder force. For the high blank holder force, the experimental results show a decreasing punch force towards the end of the punch stroke, which is not predicted numerically. This indicates that the pressure dependency of the frictional behaviour is stronger than predicted in the friction model for AA6016 with 1.0 g/m² PL39SX as shown in Figure 9.

Note that the error between the experimental and simulation results using a Coulomb friction model increases for increasing BHF, which is not so much the case when using the Triboform friction model. This also demonstrates that the tribological conditions are dependent on the process conditions, i.e. the contact pressure, which is accounted for in the friction model.

4.4 SENSITIVITY STUDY

Finally, the results of a sensitivity study are discussed. The Triboform software enables the user to numerically vary tribology parameters like the sheet roughness, tool roughness and lubrication amount. A new friction model can subsequently be generated and exported for use in FE simulations.

For the U-bend forming simulations of the AA6016 sheet material at the high blank holder force, a sensitivity study is performed by varying the amount of lubricant applied to the sheet. Additional friction models are generated for 0.8 g/m² and 1.2 g/m² PL39SX lubricant. The variation of the lubrication amount is chosen within the bounds of what can be expected in reality for 'as received' material. New forming simulations are performed using the resulting friction models. The variation of the punch force prediction is shown in Figure 12 in terms of one standard deviation.

This result demonstrates that the magnitude of the punch force prediction is highly sensitive to the lubrication amount, and that this is an important parameter to account for in future sheet metal forming simulations and robustness analyses.

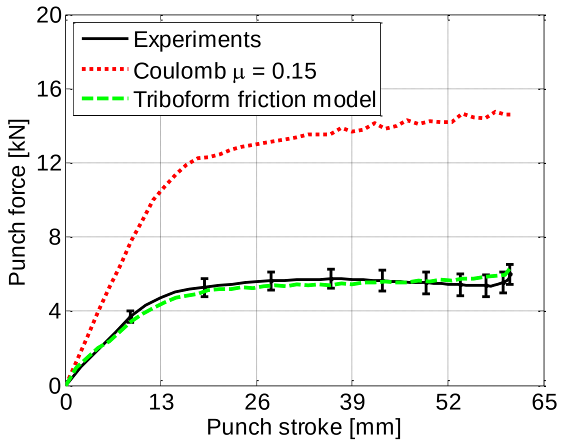

Fig. 10 *Experimental and simulation results for DX56D+Z with 1 g/m² PLS100T lubricant*

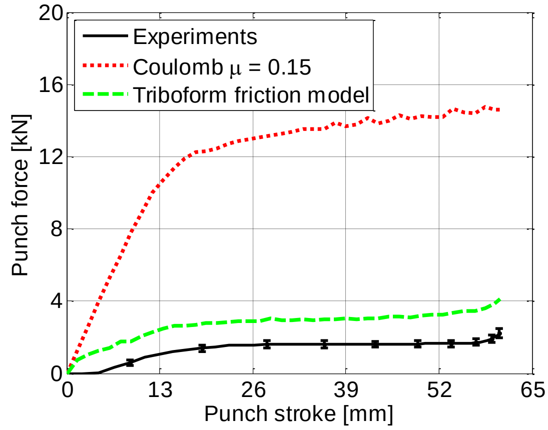

Fig. 11 *Experimental and simulation results for DX56D+Z with 2 g/m² PLS100T lubricant*

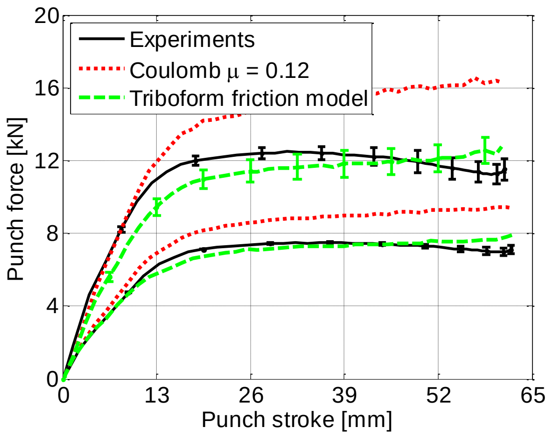

Fig. 12 *Experimental and simulation results for AA6016 with 1 g/m² PL39SX lubricant at a low BHF (bottom 3 lines) and high BHF (top 3 lines)*

5 CONCLUSIONS

From this work it is concluded that advanced friction modelling is the way forward for improving metal forming simulation accuracy, and following from that to reduce both lead time and development cost. Using the Triboform software in combination with U-bend forming simulations in AutoForm, it is demonstrated that the experimental results can be accurately predicted for all considered tribology systems.

Major benefits of the presented approach are the following. First of all, the presented friction modelling approach is based on physical models with input parameters that can be collected from a database or measured with minimal effort. It results in a fundamental understanding of the frictional behaviour per tribology system. Secondly, it reduces the demand for experimental testing and enables more accurate simulations in virtual process development. It offers Volvo Car Group the possibility to perform sheet metal forming simulations including the friction model corresponding to the tribology system as applied in stamping production. Finally, the numerical approach enables the user to perform robustness analyses including the frictional behaviour, and simulate sheet metal forming processes more accurately and realistically.

Future work will include application of the approach to the stamping process of the Side Door Inner of the new Volvo XC90. The purpose of this study is to verify the benefits for production parts and numerically study the influence of temperature dependent friction conditions and the resulting transient effects in sheet metal forming production.

6 ACKNOWLEDGEMENT

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