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Friction in Sheet Metal Forming Simulations:
Modelling of New Sheet Metal Coatings and Lubricants

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Abstract. The quality of sheet metal formed parts is strongly dependent on the tribology and friction conditions that are acting in the actual forming process. These friction conditions are then dependent on the tribology system, i.e. the applied sheet material, coating and tooling material, the lubrication and process conditions. Although friction is of key importance, it is currently not considered in detail in sheet metal forming simulations. The current industrial standard is to use a constant (Coulomb) coefficient of friction, which limits the overall simulation accuracy. Since a few years back there is an ongoing collaboration on friction modelling between Volvo Cars, Tata Steel, TriboForm Engineering, AutoForm Engineering and the University of Twente. In previous papers by the authors, results from lab scale studies and studies of a door-inner part in Volvo Cars production have been presented. This paper focuses on the tribology conditions during early tryout of dies for new car models with an emphasis on the effect of the usage of new steel material coatings and lubricants on forming results. The motivation for the study is that the majority of the forming simulations at Volvo Cars are performed to secure the die tryout, i.e. solve as many problems as possible in forming simulations before the final design of the die and milling of the casting. In the current study, three closure parts for the new Volvo V60 model have been analysed with both Coulomb and TriboForm friction models. The simulation results from the different friction models are compared using thickness measurements of real parts, and 3D geometry scanning data of the parts. Results show the improved prediction accuracy of forming simulations when using the TriboForm friction model, demonstrating the ability to account for the effect of new sheet metal coatings and lubricants in sheet metal forming simulations.

1. Introduction

The quality of sheet metal formed parts is strongly dependent on the tribology, friction and lubrication conditions that are acting in the actual production process. These friction conditions are dependent on the tribology system, i.e. the applied sheet material, coating, tooling material, lubrication- and process conditions. Although friction is of key importance, it is currently not considered in detail in stamping simulations. The current industrial standard is to use a constant (Coulomb) coefficient of friction. This

limits the overall simulation accuracy as also demonstrated in earlier work of the authors, both for a U-bend application [1] and the Volvo XC90 right rear door inner [2-3].

This paper presents a selection of results considering friction and lubrication modeling in stamping simulations of dies for the new Volvo V60, demonstrating the strong influence of tribology and friction conditions on predictions of draw-in, sheet thickness, springback and stamping forces. First the overall project approach will be outlined with details on the sheet materials, lubricants and die materials. Next, a description of the project results including a comparison between results from forming simulations using TriboForm friction models, forming simulations using a constant Columb friction and measurements on real parts. Finally, the conclusions and points of future work are described.

2. The new Volvo V60 study

2.1. Introduction
The goal of the current study is twofold. First of all, the goal is to apply the TriboForm models at Volvo Cars on dies in early try-out. The motivation for the study is that the majority of the forming simulations at Volvo Cars are performed to secure the die tryout, i.e. solve as many problems as possible in forming simulations before the final design of the die and milling of the casting. Secondly, the goal is to study the effects on stamping results of new lubricants and sheet metal coatings. The current study includes three different parts for the new Volvo V60, see Table 1 and Figure 1. The stamping dies for these parts are all manufactured at Volvo Cars tool shop in Olofström, Sweden.

Table 1. Parts included in the current study

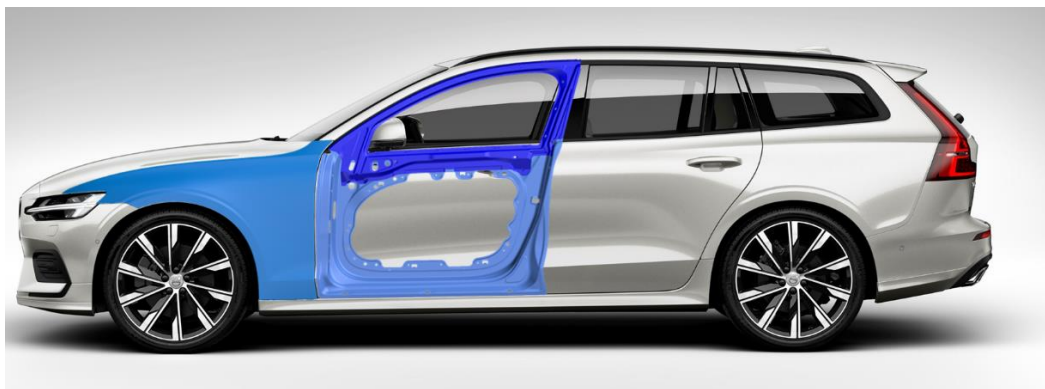| Part	Material	Coating	Pre-lube	Process
Fender	CR3	ZM 50/50+E	PLS100T	Single action
Front Door Inner	CR4	GI 50/50+U	3802	Double action
Front Door Ringframe	CR4	GI 50/50+U	PLS100T	Single action

Figure 1. The new Volvo V60 and the parts included in the study.

2.2. Sheet materials, lubricants and die materials
The sheet materials used are two mild steels, VDA239 CR3 ZM50/50-E (abbreviated CR3-ZM) and VDA239 CR4 GI50/50-U (abbreviated CR4-GI). The pre-applied lubricants used for these parts are Fuchs Anticorit PL3802-39S (abbreviated 3802) and Fuchs Anticorit PLS100T (abbreviated PLS100T). Finally, the Fender is the first exterior part with ZM coating in Volvo Cars tool shop. The main driver for ZM is increased corrosion protection. In addition a previous study on the Rear Side Door Inner of XC90, presented in [3], revealed that the ZM coatings also improves the stamping performance.

The friction conditions for the three different tribology systems have been determined according to the procedure described in [2]. The die material for all cases is GGG70L and die surface replicas were taken from dies in Volvo Cars tool room. The surface properties of the blanks were determined using sheet samples from Tata Steel. With this information and viscosity data of the lubricants, three TriboForm Libraries were created which include the friction conditions for the considered tribology systems.

2.3. Scanning of parts

The 3D geometry scanning was done with each part placed in unique fixtures used for laser trimming. The laser trimming fixtures are made of a number of 3 mm thick sheets that are 2D-profiled to accurately fit the part and then placed on a coordinate table to support the part, e.g. along the trim edge or other areas of the part where support is needed. In order to position the part, two or three bulges are stamped in the part which are used for placement over spherical pilots in the laser trimming fixture. There are also clamps in these fixtures over the locating pilots but these where not closed during the scanning performed in this study.

2.4. Sheet metal forming simulations

The sheet metal forming simulations in this study were all performed with AutoForm[plus], version 7.0.3. The material model used was BBC 2005, with material parameters determined according to the method described in [8]. The used material data is presented in Table 2 and Figure 2. The ram velocity for the single action processes was set to 50 mm/s and for the double action process it was set to 100 mm/s. This is due to the fact that the single action process was performed using a hydraulic press, while the double action one was tested using a mechanical press.

Table 2. Material data for the BBC2005 model.

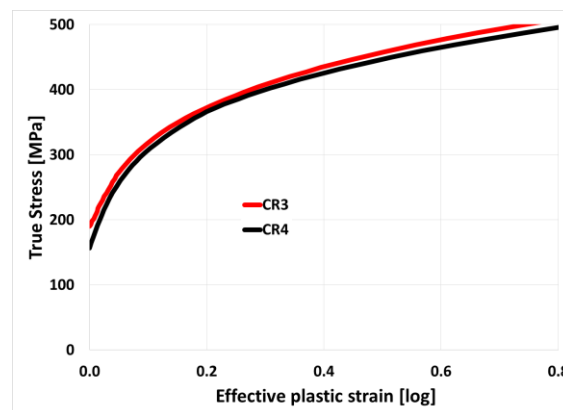|	σ_0 [MPa]	σ_{45} [MPa]	σ_{90} [MPa]	σ_b [MPa]	R_0	R_{45}	R_{90}	R_b	M
CR3	189.8	190.0	185.0	223.0	1.88	1.71	2.40	0.95	5.2
CR4	156.6	160.0	156.0	187.0	1.81	1.34	1.88	0.98	4.5

Figure 2. Hardening curves used in the forming simulations.

The springback analysis in AutoForm was defined as a Real Measurement process step. The support surfaces of the laser trimming fixture were replaced by contact points where clamps were defined. The spherical pilots were defined as tools and positioned such that they position the part but did not carry any load. The coordinates of the clamping points were defined by measuring the distance between the reference surfaces of the forming simulation and each support surface of the laser trimming fixture in

CATIA V5. Subsequently, the simulation of springback was performed in two steps. First, all contact points were imported into AutoForm and used as supports, i.e. not closed. After this initial simulation, all clamps that were not in contact with the sheet are removed. Also, some of the remaining clamps were closed to stabilize the simulation but without imposing any rigid body movement with this operation. The second model was then solved and checked so that the requirements described above were fulfilled, i.e. no loads on pilots and no rigid body movements during clamping.

3. Results and discussion

3.1. Tribology systems
The left plot in Figure 3 displays the three tribology systems used in this study and the corresponding friction models as a function of contact pressure and sliding velocity. As a comparison, the models from the study presented in [2-3] are displayed in the right plot in Figure 3. The three different systems used is this study are very similar and furthermore, the friction coefficients for each model is much lower than 0.15 which is today's standard value for Coloumb friction at Volvo Cars. Only at low contact pressures, the CR3-ZM model and the CR4-GI model with PLS100T has a higher friction coefficient than 0.15. Another interesting observation is that both models for CR4-GI in the current study have similar or slightly lower friction behavior than the models used in the study presented in [2-3]. Since the die surfaces in [2-3] are either hardened or chrome plated, with a lower surface roughness and the lubrication amount of 2 g/m^2, one should expect lower friction coefficients for these models than the models used in this study. However in [2-3], the pre lubricant is only a rust protection oil which has less or no positive effects on the stamping operation. Other positive effects of the first and second generation pre-lubricants are less migration and sagging over time compared to rust protective oils.
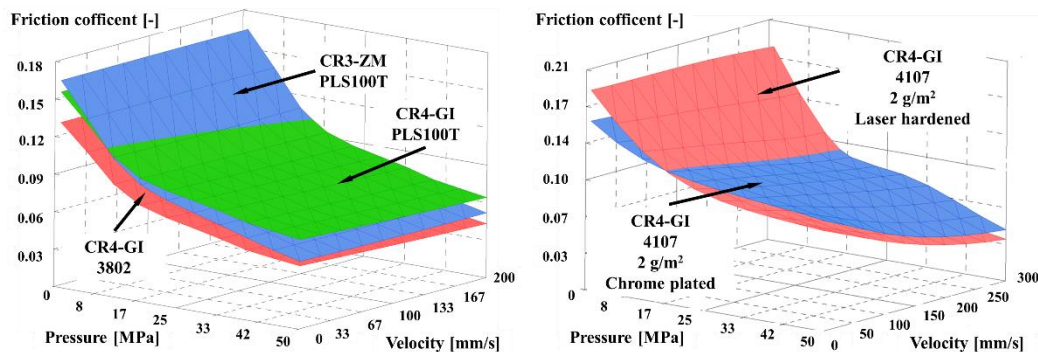

Figure 3. The three tribology models used in this study (left) and the tribology models from [2-3] (right).

The varying friction conditions will have an impact on almost all interesting results of a sheet metal forming simulation, i.e. draw-in, major and minor strains, springback and stamping forces. By comparing simulation results using the tribology models in the left part of Figure 2, with simulations using a constant friction coefficient of 0.15 and measurements on real parts from die try-out, the impact on each stamping process result can be quantified.

3.2. Draw-in
In this section the final position of the blank edge and pre-cut holes are compared with scan data of parts from the die try-out. This comparison reveals that the predicted blank edge position for the Fender and the Front Door Ringframe, is very similar, regardless if the TriboForm models are used or a constant friction coefficient of 0.15 is used. Furthermore, the accuracy of these predictions are generally very good, i.e. a small difference between measured and predicted edges are observed.

The results for the door inner is completely different. The CR4-GI with 3802 friction model has a much larger draw-in compared to the same simulation using a constant friction coefficient of 0.15. The maximum difference is almost 30 mm is some areas. The accuracy of the predictions is different in different areas of the part, see Figure 4. Along the lower edge of the two doors, the constant friction model has a higher accuracy of the draw in prediction. In these areas, the TriboForm model are overestimating the draw-in with up to 20 mm. The draw-in of the other edges, i.e. the front and rear edges of the doors, is underestimated by both friction models, but the TriboForm model is closer to the scanned data. Finally, the final edge of the pre-cut holes in blank is predicted with higher accuracy with the TriboForm friction model than using a constant friction.
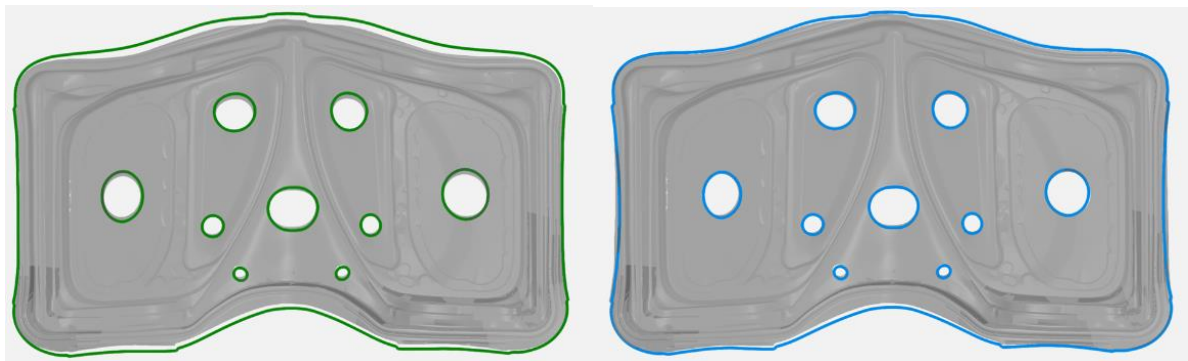

Figure 4. Scan data (grey) compared with predicted edges using μ=0.15 (left) and the TriboForm model for CR4-GI and 3802 (right).

This last conclusion indicates that the friction conditions for the part of the blank that are in contact with the punch is more accurately modelled with the TriboForm model than using a constant friction. In this area, the elastic die and punch deformations are small and the FE-model therefore corresponds well with deformed geometries in reality. On the other hand, the draw-in of the edges is influenced by both the pressure distribution under the blank holder and the actual gap between the male and female part of the draw beads. These two parameters are in turn in reality influenced by elastic deformations of the blankholder, which in a double action forming process varies quite a lot over the blankholder. The effect of these elastic deformations of the blankholder on the draw-in can only be analysed in detail by performing sheet metal forming simulations using accurate material and friction models coupled with a structure analysis of the current die design and press system.

3.3. Sheet thickness after forming

Since no strain measurements were available, the second best option was to compare sheet thickness measured in the final parts with the prediction from simulations using different friction models. The thickness measurements on the parts were made with an ultrasonic device. For the Ringframe part, both simulation models predict almost identical sheet thickness and these values agreed well with the measurements on the real part.

The predicted sheet thickness for the Fender is also generally very similar using the TriboForm model or using a constant friction coefficient. However, a closer inspection reveals that there are two areas of the part where the two simulation models predict quite different thicknesses, see Figure 5. In both these areas, the values predicted using the TriboForm model are closer to the measurements made on the real part than the results using a constant friction. In one point, the difference in sheet thickness between measurements and predicted values using a constant friction coefficient is 0.1 mm which is a large deviation. Worth mentioning is the fact that the predicted thickness in that point is smaller than the measured one, i.e. the part is closer to failure limit in the simulation than in try-out if one uses a constant coefficient of friction of 0.15. These results are encouraging and interesting since the draw-in for the two different friction models were very similar.
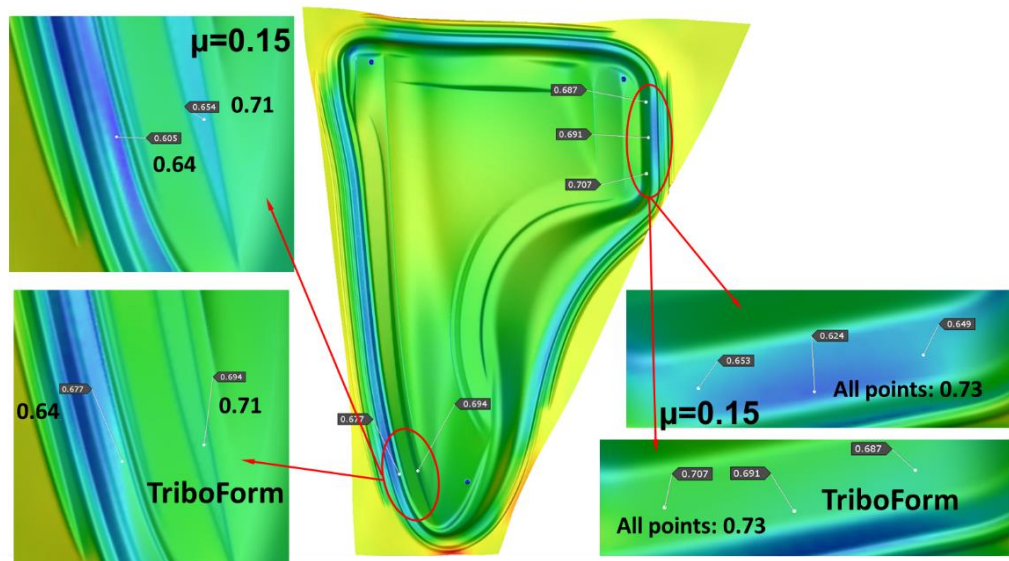
Figure 5. Predicted and measured sheet thickness for the Front Fender part.
Measured values plotted next to AutoForm values.

The difference in predicted sheet thickness for the Front Door Inner is slightly larger than for the Fender. For this part, the values predicted using the TriboForm model are closer to the measured ones than the values predicted using a constant friction coefficient, see Figure 6. Also in this comparison, there is one point where the difference between the measurements and predicted values using a constant friction coefficient of 0.15 is more than 0.1 mm. This point is marked with a red circle in Figure 6. However, one should keep in mind that this part has the least accurate prediction of the draw-in, which influences accuracy of the sheet thickness prediction. However, in the area where the marked point is located, the TriboForm results predict the draw-in more accurately. For this point, it is therefore safe to claim that the TriboForm prediction is more accurate.
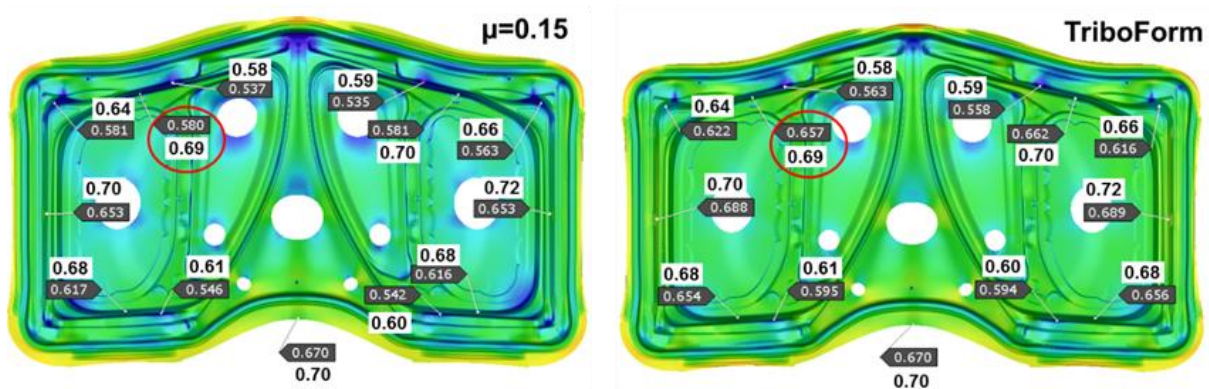

Figure 6. Predicted and measured sheet thickness for the Front Door Inner part.
Measured values plotted next to AutoForm values.

3.4. Part shape after forming and springback
The comparison between scanned 3D geometry data and the simulation prediction was made in GOM Correlate Professional. Both the scan data and the simulated data was imported into the software and then the scan data was placed on top of the simulation data with best fit alignment.

The comparison of scanning and simulation data for the Front Door Inner reveals that the accuracy of the prediction are acceptable in large parts of the part. In some areas the deviations between simulation results and the scanning data are larger and for some of these areas the TriboForm predictions are more accurate. In others areas, the predictions using a constant friction coefficient are more accurate. Once again one should keep in mind that this part has the least accurate prediction of the draw-in, which also influences accuracy of the springback prediction.

The comparison of scanning and simulation data for the Front Door Ringframe and the Fender shows two clear trends. Firstly, these predictions are more accurate than the prediction for the Front Door Inner. For the Front Door Ringframe, the prediction is very accurate, see Figure 7. Secondly, the TriboForm prediction is slightly more accurate than prediction using a constant friction coefficient, see Figure 7.
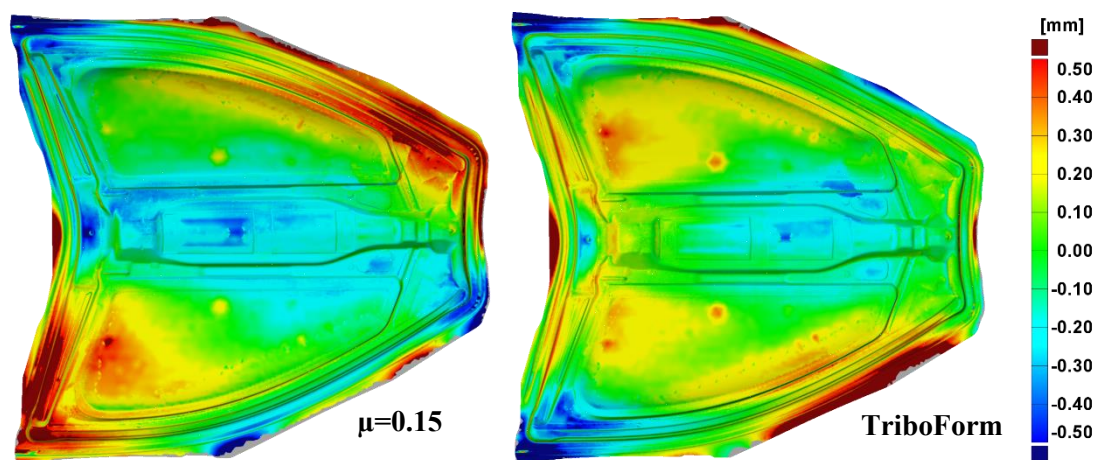

Figure 7. Distance between predicted shape after forming and springback from forming simulations and scan data of the Front Door Ringframe.

3.5. Punch forces

No punch forces were measured during try-out, so this comparison is only made between simulation results from the two friction models. For the Front Door Ringframe, the punch force using the two different friction models are almost identical. For the other two parts, the TriboForm model predicts a 10 % lower punch force than the model using a constant friction coefficient.

4. Conclusions

There are a number of interesting conclusions that can be drawn from this study. First of all, the TriboForm results indicate that the lubricants of the first and second generation used in this study will improve stamping robustness. Comparing the data for the TriboForm models in this study with data from previous studies with hardened and smoother die surfaces but only with a rust protective lubricant, the friction coefficients are similar or slightly lower. In addition, other positive effects (such as migration and sagging) of the new pre-lubricants have not been analysed in this study..

Another interesting observation is that, using the TriboForm models in stamping simulations, results in predictions of draw-in, sheet thickness and part shape after forming and springback that are at least as accurate as using a constant friction coefficient of 0.15. In fact, in the majority of the comparisons between simulation and measured data made in the study, the simulation accuracy is higher using the TriboForm models than using a constant coefficient of friction. This is the same conclusion as the authors have made previously in studies of both lab scale tests and parts in running production [1-3]. From the combined results of these studies, it can be concluded that the TriboForm software and resulting friction models are applicable on all different types of parts and scenarios present in sheet metal forming.

Another very interesting observation can be made by comparing the results for the Front Door Ringframe and the Front Door Inner. The forming process inputs for these two parts are identical, except for the type of pre-lubricant, the draw depth of the parts and the press-type used. By studying the results, the conclusion is that for the Front Door Ringframe, a constant friction coefficient of 0.15 is actually producing accurate results. On the other hand, for the Front Door Inner the constant friction coefficient should be reduced in order to improve draw-in and thickness predictions. The difference in pre-lubricant cannot totally explain the difference in constant friction coefficent as the two TriboForm models are similar. The draw depth of the Front Door Inner is more than two times the draw depth of the Front Door Ringframe and this has an impact on the amount of draw-in. A larger draw-in will results in a higher relative velocity between the sheet and die surfaces which reduces the friction coefficient. Also the use of a single or double action process does have an influence.

Finally, a constant coefficient of friction can be seen as an average value that can be used to approximate friction conditions for different tribology systems and forming processes in a good way and thereby resulting in a good simulation accuracy. An implication of this statement is that in order to achieve a higher simulation accuracy, you can try to determine an optimal constant friction coefficient for each tribology system and forming process. This is an almost impossible task since values are needed in the engineering phase that ideally can't be determined until after the die try-out. The solution instead is to determine and use advance friction models, like the TriboForm models, that accurately predict friction conditions for the actual tribology system used giving accurate results, independently of the material and forming process.

5. Future work
The next step at Volvo Cars is to apply the TriboForm model in sheet metal forming simulations of all parts manufactured in the Volvo Cars tool shop. This must be done in a controlled manner and will be done gradually over a number of future car projects. A parallel track for future investigation is to include the variation of oil amount over the sheet in the simulations, e.g. as measured in production, and study the effects of this variation on part quality. The influence to different blank holder models and numerical setting in AutoForm should also be evaluated.

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