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Friction in sheet metal forming: influence of surface roughness and strain rate on sheet metal forming simulation results

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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 body parts at Volvo Cars, both parts in early tryout for new car models as well as parts in production have been presented. However, the introduction of a new friction model in the sheet metal forming simulations forces the user to gain knowledge about accurate values for new input parameters and question current modeling assumptions. This paper presents results from studies on the influence on the sheet metal forming simulation results from stamping die surface roughness and introduction of strain rate sensitivity in the sheet material model. The study will use a FE-model of a part presented in previous papers.

Keywords: Sheet Metal Forming Simulations; Material modeling; Friction modeling; Tribology

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1. Introduction

Accurate sheet metal forming simulations are highly needed for developing cost effective production processes for automotive panels. Effectiveness increase of the stamping process development enables shorter development time, increased material utilization and less scrap and thereby provides a significant contribution to the current efforts of the automotive industry to reduce the environmental burden of industrial processes.

Significant accuracy increase in sheet metal forming finite element simulations can be obtained by incorporation of advanced friction models and advanced material models as has been demonstrated by the research of Volvo Cars in collaboration with Tata Steel, TriboForm Engineering, AutoForm Engineering and the University of Twente. Both model tests as well as car body parts in both try-out and production conditions have been studied and the conclusions has been presented in [1-4].

The advanced friction model introduced by TriboForm predicts the dependence of the friction coefficient on contact pressure, sliding velocity, plastic deformation and temperature. It provides a more realistic description of the local contact condition in the simulation as compared to the constant Coulomb friction model, which is currently used as the industrial standard. The TriboForm model also introduces parameters defining the tribology system: the tool material and surface roughness, the sheet material, sheet surface roughness and sheet coating type and finally, the lubricant type and quantity. Therefore, the use of the model requires additional assumptions for all these parameters. Typically, in a test die, the variation of the sheet metal roughness is small and can be neglected while the lubricant quantity can be maintained at a chosen constant value for a selected lubricant. On the other hand, in a die set used in industrial applications, the active surfaces coming in contact with the sheet metal might present both variations of surface roughness and differences in material type. It is common to use chrome plating or surface hardening treatments as requested by the industrial application. Consequently, the actual tribology system of a die set needs to be defined for each contact surface depending on surface material and the local surface roughness.

The extra parameters offered by the advanced friction and material models needs to be careful selected and a number of simplifying assumptions is usually needed in order to keep the model manageable. At the same time, a sensitivity analysis in order to determine the most important parameters would appear as an option but the overall complexity prevents incorporation of all aspects in one model. A gradual approach is preferred in which the addition of new parameters is justified by estimating the significance of the differences observed between simulation and experimental results while performing sensitivity analysis on a reduced number of parameters.

This paper presents a model based study of a door inner panel. Characteristic for the part chosen for this study is the complicated geometry typically found in closures applications where the challenge is to find a balance between preventing splitting and controlling wrinkling while maximizing the part depth. The first studies performed on this part with the most simple variants of the advanced TriboForm models, no strain rate sensitivity and one tribology system for all active surfaces indicated the potential for further accuracy increase. The present study describes the effects of the of tool roughness and material strain rate sensitivity effects on simulations predictions.

2. Current study

2.1. Part production at Volvo Cars

The part that was used in [2-3], i.e. the Rear Door Inner for Volvo X90 is also used in this study. The part is produced in a mechanical transfer press-line at Volvo Cars in Olofström, Sweden. The corresponding velocity profile of the press line has been recorded and implemented in the forming simulations. The blank is a contour cut from a 1700 mm wide coil and the pitch is 1553 mm. The stroke rate is set to 8 strokes/min. The sheet material is a VDA239 CR4 GI sheet material with a thickness of 0.7 mm, EDT surface finish and delivered by Tata Steel. The sheet material is delivered with a Fuchs Anticorit RP4107S lubricant. Measurements in production have shown that the lubrication amount ranges between 0.7 g/m^2 and 2.2 g/m^2 on both sides of the sheet. An average value of 2.0 g/m^2 will be used in this study. The tooling material is nodular iron GGG70L. The tools are hardened at the positive tool radii and chrome plated at selected areas, see also Table 2.

2.2. Sheet Metal Forming Simulations

All sheet metal forming simulations in this study has been performed with AutoForm^{plus}, version 7.0.4 and the FE-model is displayed in Fig 2. The actual tooling geometries have been determined by 3D scanning. After the scanning, an FE-analysis of the complete die and press structure loaded with the blank holder force used in production has been performed and the deformed scanned surfaces in that FE-analysis after blank holder closing are used in the sheet metal forming simulations, see [5] for more details. The material model used was BBC 2005, with material parameters determined according to the method described in [10]. The used material data is presented in Table 1 and Fig 1. The different settings for tool surface hardening, coating and S_a-roughness value in each part of the die in each simulation are presented in Table 2. Both GI- and ZM-coated blanks are included in the study.

Table 1. Material data for the BBC 2005 material model.

	σ_0 [MPa]	σ_{45} [MPa]	σ_{90} [MPa]	σ_b [MPa]	R_0	R_{45}	R_{90}	R_b	M
CR4	156.6	160.0	156.0	187.0	1.81	1.34	1.88	0.98	4.5

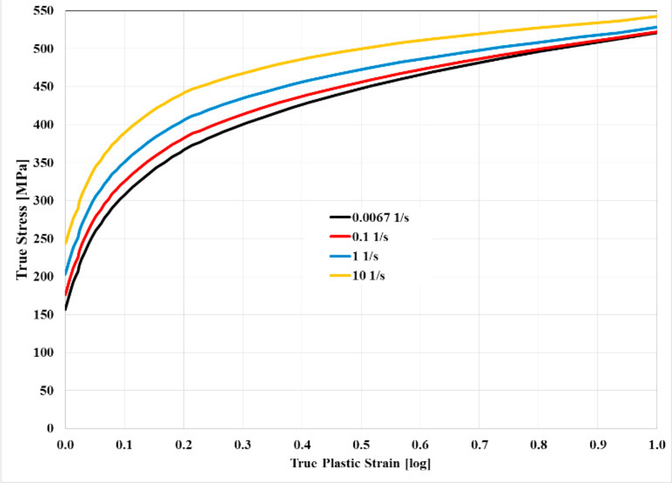


Fig 1. Hardening curves used in the forming simulations.

Table 2. Tool surface hardening, coating and S_a-value used in the different simulations.

Simulation	Upper Binder Lower Binder [µm]	Die Punch [µm]
Reference	Laser Hardened, 0.45	Chrome Plated, 0.35
1	Laser Hardened, 0.35	Chrome Plated, 0.35
2	Laser Hardened, 0.75	Chrome Plated, 0.35
3	Laser Hardened, 0.45	Chrome Plated, 0.20
4	Laser Hardened, 0.45	Chrome Plated, 0.50

3. Results and Discussion

3.1. The Reference Model

In papers [2-3], only one friction model was used for all die surfaces due to limitations in the interface between TriboForm Analyzer and AutoForm at that time. However, in the die used in production, the die surface is divided into two areas, the upper binder is laser hardened and the die surface is chrome plated. The lower binder is also laser hardened. The first step in this study was therefore to include these modifications in the FE-model in order to bring it closer to the die used in production. The simulation results from this modified model was then compared with the simulation results from the previous FE-model used in [2-3]. For both GI- and ZM-coated blanks, it was concluded that major strains increased slightly while the draw-in was slightly reduced. For the remainder of this study, the updated model is the reference.

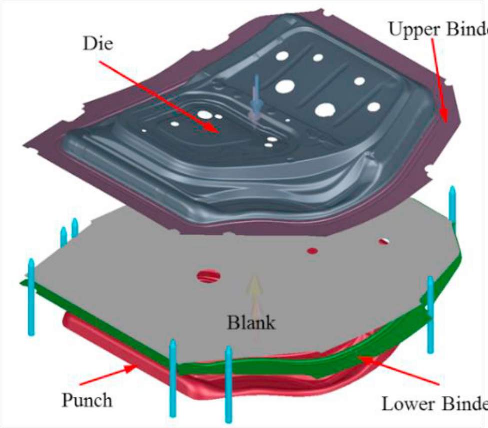


Fig 2. The AutoForm FE-model used in the study. The different friction surfaces in Table 2 are also displayed. The Upper Binder and the Die is a single structure moving as one unit in the simulation.

3.2. Influence of the upper and lower binders tool surface roughness on the results

The set-up of Simulations 1 and 2 in Table 2 are designed to study the effects on the simulation results of the tool surface roughness on the upper and lower binders. The friction forces on these surfaces together with the draw beads are controlling the flow of the sheet material during the stamping process. One could therefore assume that the S_a-value will have a large influence on the simulations results, in this case the major strain and the draw-in. For the GI-system, this assumption is confirmed, at least partly. Major strains and draw-in in Simulation 1, which uses a low S_a-value, is similar to results with the reference model. On the other hand, in Simulation 2, the major strains are higher and the draw-in is lower than for the reference model. The difference in major strain between Simulation 1 and 2 and the reference model are displayed to the left and in the middle in Fig 3. A positive value in Fig 3 indicates an increase of the major strain compared to the reference model using the S_a-value in that particular simulation. Similarly, a negative value indicates a decrease of the major strain compared to the reference model using the S_a-value in that particular simulation.

The results form Simulation 1 and 2 using a ZM-system shows the same trends, but the magnitude of the differences is smaller than for the GI-system, see right plot in Fig 3.

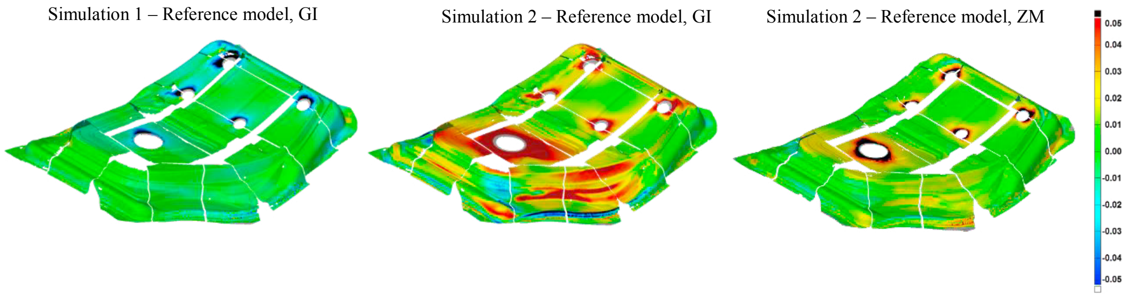


Fig 3. Difference in major strain between Simulation 1 and the reference model with the GI-system (left), Simulation 2 and the reference model with the GI-system (middle), Simulation 2 and the reference model with the ZM-system (right).

Studying all these results, two conclusions can be made. Firstly, the response from both the GI- and ZM-system is non-linear. A binder surface with a high S_a-value result in higher major strains and lower draw-in compared to a binder surface with a low S_a-value. However, at certain S_a-value, the difference in results becomes small for further reduction of the S_a-value. The second interesting conclusion is that the effect described above is more pronounced for the GI-system.

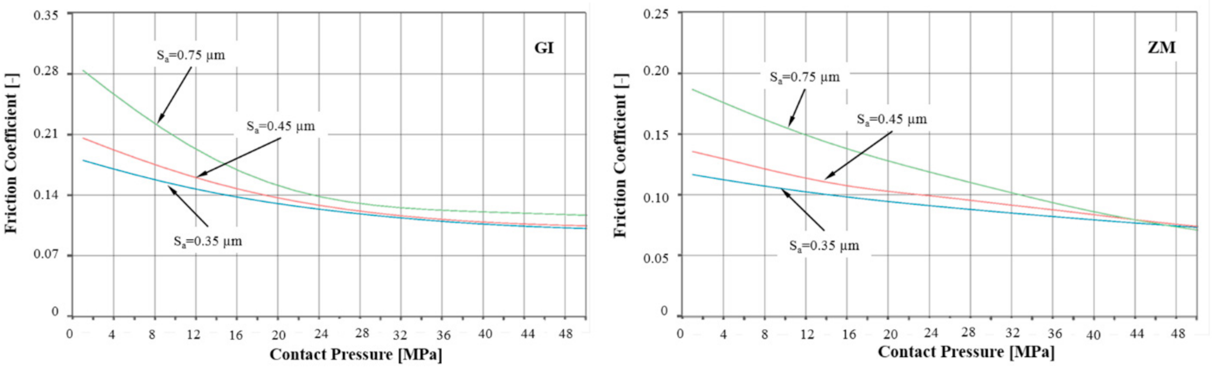
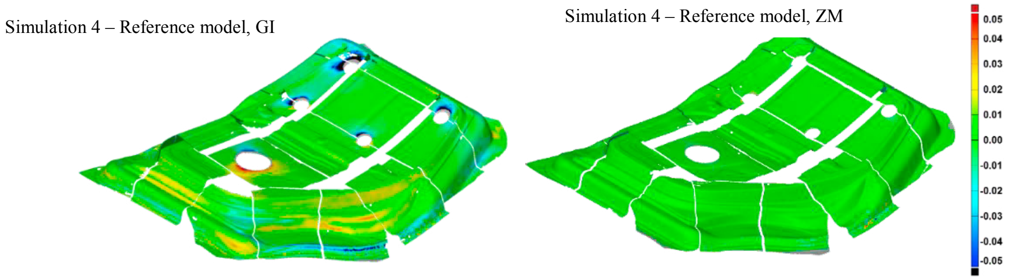


Fig 4. Friction coefficients as function of contact pressure for different S_a-values for the GI-system (left) and ZM system (right) in Simulation 1 and2.

3.3. Influence of the die and punch tool surface roughness on the results

The set-up Simulations 3 and 4 in Table 2 are designed to study the effects on the simulation results of the tool surface roughness of the die and the punch. On these surfaces, there are less displacement of the sheet material, at least compare to the upper and lower binder surfaces. The major deformation mode is instead bending the sheet and/or stretching sheet material between two radii. The assumption therefore is that the surface roughness on these surfaces will a less influence on the simulation results compared to the tool surface roughness on upper and lower binder and this is confirmed for both the GI- and ZM-system. Once again, the simulations with the highest S_a-values are generating the largest differences in major strain and draw-in compared to the reference model, see Fig 5, and for these simulations are the difference larger for the GI-system than for the ZM-system.


Simulation 4 – Reference model, GI

Simulation 4 – Reference model, ZM

Fig 5. Difference in major strain between Simulation 4 and the reference model with the GI-system (left), Simulation 4 and the reference model with the ZM-system (right).

The pressure dependency of the two different systems in Simulations 3 and 4 are displayed in Fig 6. These values are also valid for a temperature of 21°C, no straining of the sheet material and 1 mm/s relative velocity between the sheet and die surface. The friction coefficients for the tribological systems in Simulation 3 and 4 are similar to those displayed in Fig 4, but the current systems have lower friction coefficients. For the ZM-system, the difference friction coefficient is small for the three different S_a-values. The similarities between Fig 4 and Fig 6 implies that also the tool surface roughness on the die and punch should have an influence on the results, at least for high S_a-values.

However, there is also another fact that must be considered, namely the contact pressure at different location in the stamping die. The contact pressures are high in the draw beads and low on the other parts of the upper and lower binder. On the die and punch are also the contact pressure high. Therefore should the focus be on differences at low pressures in Simulations 1 and 2 and Fig 4, while the focus should be at high pressures in Simulations 3 and 4 and Fig 6. In Fig 4, the largest differences in friction coefficients are at low pressures and this result in a large effect on the major strains and the draw-in. In Fig 6, the differences between friction coefficients for the three different S_a-values is small at high contact pressures which then explains the small effect on the simulation results for Simulation 3 and 4.

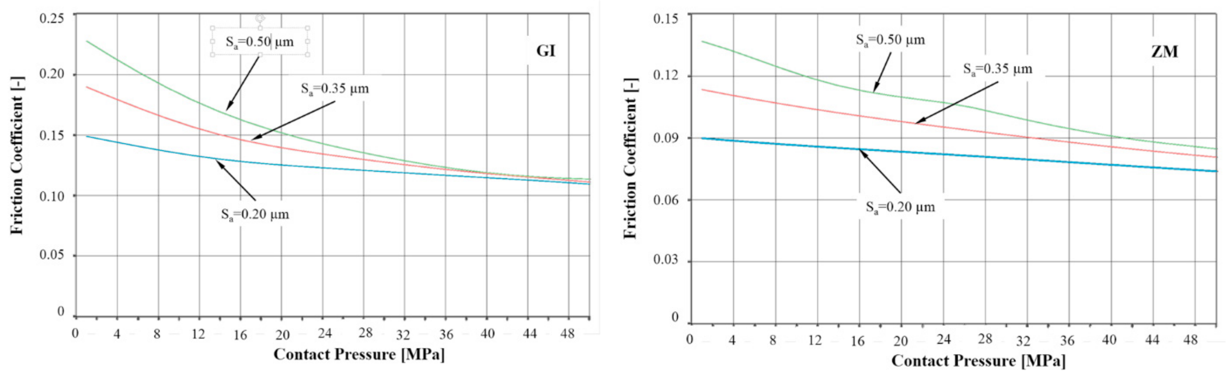
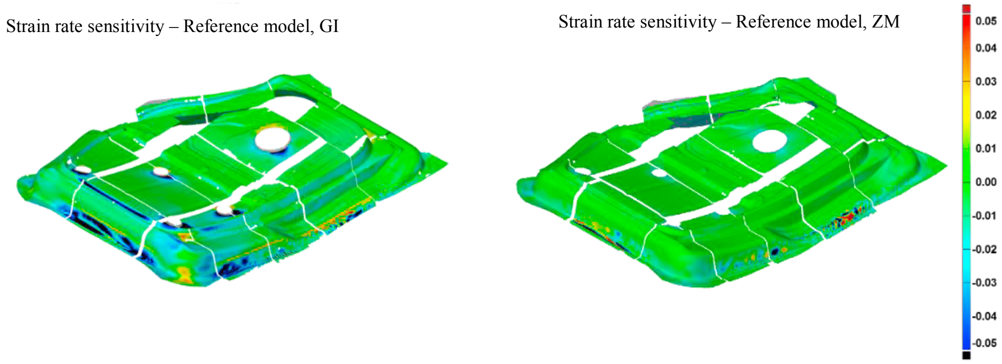


Fig 6. Friction coefficients as function of contact pressure for different S_a-values for the GI-system (left) and ZM system (right) in Simulation 3 and 4.

3.4. Influence of strain rate sensitivity on the results

The reference model, using both the GI- and the ZM-system, has been simulated with a material model that includes a positive strain rate effect, i.e. an increase of the strain rate will increase the strength of the material. The idea is that this will reduce the major strains in the part and in Fig 7 are the difference in major strain with and without strain rate sensitivity for the two tribology systems presented.


Strain rate sensitivity – Reference model, GI

Strain rate sensitivity – Reference model, ZM

Fig 7. Difference in major strain for the reference model including strain rate sensitivity compared to without strain rate sensitivity. The difference for the GI-system is displayed in the left plot and the difference for the ZM-system is displayed in the right plot.

The results in Fig 7 are interesting. Using the GI-system, the major strain is reduced, but not in all areas. In fact, the major strain in the majority of the part is almost the same with and without strain rate sensitivity. However, one area with a large reduction is in the door bow in the upper part of the door. For ZM-system, there is hardly no difference in the major strain between the strain rate sensitive model and the reference model. In order to try to understand these results, the plastic strain rate in the two simulations are compared and presented in Fig 8.

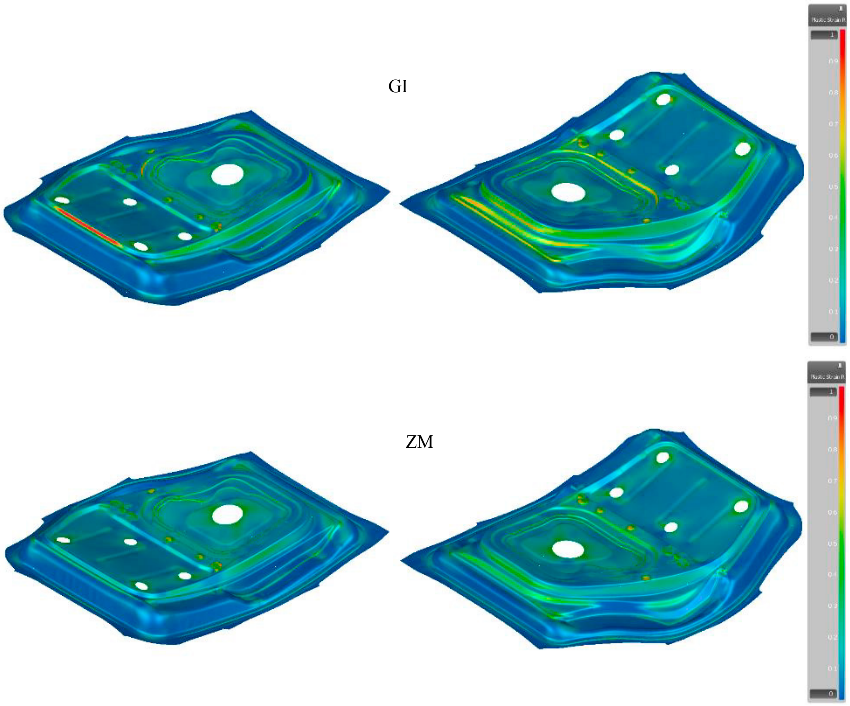


Fig 8. Plastic strain rate in the sheet mid surface at the end of the forming operation in the model with strain rate sensitivity for the GI-system (top) and the ZM-system (bottom).

The results in Fig 8 is showing significant differences in strain rate, depending on if the GI- or the ZM-system is used. In general, the strain rates are higher with the GI-system. The area in the door bow is once again showing the largest differences, almost five times higher strain rates with the GI-system than with the ZM-system. In some other areas, e.g. in the lower part of the door, the strain rate are twice as high for the GI-system compared to the ZM-system. If the same comparisons of the plastic strain rates are done for the reference model, the differences between the GI- and the ZM-system are similar to those presented in Fig 8, i.e. the introduction of strain rate sensitivity is not the reason for these differences displayed in Fig 8. Instead, it is once again differences between the two tribology models that generate the results presented in Fig 8. This was not at all expected, but nevertheless important and interesting.

4. Conclusion and further work

The tool surface roughness has a significant effect on simulation accuracy as the differences in punch, die and binder areas tribology systems results in different balance between stretching in the punch area and material flow into the die cavity. The increase of the binder surface roughness while the punch and die roughness are kept constant results in significant higher restraining and is explained by the friction coefficient increase with increasing the tool surface roughness for the GI system. The effect is also present but it is smaller for the ZM system.

Similarly, the die and punch tools surface roughness variation study indicates a more sensitive GI system as compared to the ZM system. In this case, the effects are smaller as compared to the binder variations and demonstrates the non-linearity of the tool surface variation effects originating from both friction model behavior and part geometry complexity.

The studied model reacts also in the case of incorporating the strain rate sensitivity as compared to the more simple situation of a rate independent model. The effects are part location dependent with the areas experiencing large sliding in the part wall more affected as compared to the area in the punch region. Again, the two tribology systems appear to behave differently with the ZM-system less sensitive for this effect as compared to the GI-system.

The similar behavior of the strain rate sensitivity and the reference model suggests that the most important effect originates from the friction model. This observation stresses the need of both accurate friction model data parameters and also the need for further investigations toward sliding speed effects characterisation.

This study illustrates the importance of tool roughness control in sheet metal forming. From an experimental perspective it indicates both a challenge and an opportunity. Non-uniform tool surface roughness might result in significant differences between the predicted behavior as compared to the experimental behavior during tool try-out or part production and would require additional trial and error experiments in order to obtain the desired restraining of the material flow needed for obtaining good quality pressed parts. At the same time as the effect appears to be sliding velocity dependent, the results of the tests might be significant different between series production and tool try-out conditions and contributing in this way in a negative way to the process of die set conditioning.

From the simulation perspective, the tool surface roughness effects can increase the difficulty of assessing the simulation accuracy while comparing the simulation results to experimental draw in and strain distribution measurements.

The opportunity suggested by this study originates form the fact that tool roughness can be used as an additional parameter to control material flow, provided that it is maintained between acceptable limits in order to prevent undesired phenomena as galling and the associated tool pollution. Modern additive manufacturing techniques available today might be used to modulate the tool surface roughness in a way that would result in a good part quality and higher forming depth.

Finally, a comment on the effects of the used coating system. The use of novel coatings on the sheet metal for automotive applications like the ZM-system, which is less sensitive to tool roughness and sliding speed, provides advantages. One example is a possibility for reducing the costs associated to tool manufacturing and production ramp up at the start of a new car project and the behavior of the ZM coating system provides a good basis for further increase of the manufacturing productivity.

The future work will involve similar studies as the current one on different parts and different tribology systems. One interesting case would be to study the sensitivity to tool surface roughness for sheets with pre-lubs of the 1st and 2nd generation that now are available and used in the automotive industry.

References

[1] M. Sigvant, J.Hol, T. Chezan, T. van den Boogaard, Friction modeling in sheet metal forming simulations: Application and validation on an U-bend product, Proceedings of FTF 2015, Zurich, Switzerland.

[2] M. Sigvant, J. Pilthammar, J. Hol, J.H. Wiebenga, T. Chezan, B. Carleer, A.H. van den Boogaard, Friction and lubrication modeling in sheet metal forming simulations of a Volvo XC90 inner door, IOP Conference Series: Material Science and Engineering 159 (1) (2016).

[3] M. Sigvant, J. Pilthammar, J. Hol, J.H. Wiebenga, T. Chezan, B. Carleer, A.H. van den Boogaard, Friction in sheet metal forming: Simulations of the Volvo XC90 inner door, Proceedings of FTF 2016, Ohlstadt, Gemany.

[4] M. Sigvant, J. Pilthammar, J. Hol, J.H. Wiebenga, T. Chezan, B. Carleer, A.H. van den Boogaard, Friction in Sheet Metal Forming Simulations: Introduction of New Sheet Metal Coatings and Lubricants, Proceedings of IDDRG 2018, Waterloo, Canada.

[5] J. Pilthammar, M. Sigvant, S. Kao-Walter, Introduction of elastic die deformations in sheet metal forming simulations, International Journal of Soild and Structures, 151 (2018) 76-90

[6] R. Grueebler, P. Hora, Temperature dependent friction modeling for sheet metal forming. International Journal of Material Forming, 2 (2009) 251–254.

[7] M. Ludwig, C. Müller, P. Groche, Simulation of dynamic lubricant effects in sheet metal forming processes. Key Engineering Materials, 438 (2010) 171–178.

[8] J. Hol, V.T. Meinders, M.B. de Rooij, A.H. van den Boogaard, Multi-scale friction modeling for sheet metal forming: The boundary lubrication regime. Tribology Int., 81 (2014) 112–128.

[9] J. Hol, V.T. Meinders, H.J.M. Geijselaers, A.H. van den Boogaard, Multi-scale friction modeling for sheet metal forming: the mixed lubrication regime. Tribology Int., 85 (2015) 10–25.

[10] D. Banabic, B. Carleer B, D.-S. Comsa, E. Kam, A. Krasivskyv, K. Mattiasson, M. Sester, M. Sigvant, X. Zhang, Sheet Metal Forming Processes, Constitutive Modelling and Numerical Simulation, Springer, (2010).