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Prediction of sheet metal part production robustness using advanced tribological models, thermo-mechanical modelling and stochastic FE-simulations

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Abstract. The automotive industry is currently facing increasing sustainability demands in order to reduce the environmental impact of their businesses and products. As a part of these demands, reduced amount of scrapped parts in current production is favourable since it contributes to both an increased productivity as well as improved environmental sustainability. Furthermore, in the near future, more sustainable sheet metals will be introduced in the production which could have a larger variation in properties which could increase the number of scrapped parts. These new demands and sheet materials have been the starting point for the study presented in this paper. It is based on results from a Volvo Cars stamping plant for a part in production that has experienced production disturbances. The information from the press shop stated which combinations of sheet metal coatings and lubricants that gave a robust production and which combinations that generated an unacceptable number of scrapped parts. These different tribological systems have then been simulated using the AutoForm R12 Sigma software with TriboForm models of the used tribological systems in the press shop. The simulations are also using the Cold Forming with Temperature Effects functionality in AutoForm R12 which makes it possible to also include the effects of temperature increase in the stamping die during the production of the part.

1 Introduction

Today, the automotive industry faces increasing sustainability demands. In this paper, the word sustainability has a very broad meaning. Environmental sustainability, i.e. actions that reduce the carbon footprint of the industry and also increase the reuse of materials, is obviously included. But also financial sustainability, which includes reduced production disturbances and production down-time in order to maximise productivity and profit, is also included. The third type of sustainability included is sustainability when it comes to human resources, i.e. providing good working environment and also secure the access of skilled personnel in the future, even though the demography is changing.

These three main types of sustainability are also interacting and attempts to improve one type could have negative effects on one or both of the other two. For example, one way to improve the environmental sustainability of sheet metals used in the automotive industry is to increase the amount of scrap in the sheet material. This could in the long run lead to larger variation in mechanical properties, which in turn will lead to increased production cost due to production down-time and scraped parts. This will also put pressure on the personal in the production and maybe they need to work overtime to be able to deliver the ordered number of parts. In the future it could also be hard to find skilled personal to solve the problems due to a decreasing population.

A way to solve this conflict and increase the environmental sustainability without negative effects on the other two, is to apply FE-simulation of sheet metal forming also to production disturbances in order to find solutions to the problems faster and in the long run even control the production via a digital twin or a digital shadow of the press line. In order to be able to do this, the CAE-engineer has to create an advanced model, including several improvements of sheet metal forming simulations that has been developed and commercialised the last two decades. The first improvement is stochastic simulations. This is a methodology where one or more input parameters are systematically varied and then a large number of simulations are performed with different types of combination of input parameters. The large advantage with stochastic simulations is that the CAE-engineer now is able to evaluate how robust a forming process is and also quantify the expected scrap rate. See [1]-[4] for previously published examples of stochastic simulations in sheet metal forming.

But the accuracy of these predictions are as all other types of FE-simulation depends on both the accuracy of the model and the accuracy of the input data. One phenomenon that historically has been hard to model accurately is the tribology conditions in the sheet metal forming process. During the last decade, new friction models has been presented that improves the accuracy. See [5]-[10] for examples of these new friction models for sheet metal forming. One of the inputs to a friction model could be the temperatures in the different interfaces between the sheet and stamping die surfaces. In normal production, these temperatures increases stroke by stroke until a steady state temperature is reached, see also [8, 11]

2 Current study

2.1 Introduction to the study

In this paper, the authors will use three different features of AutoForm Forming R12 to study the production of Wheel House Outers Volvo XC60. These there features are:

- AutoForm Sigma, which is a package that can define, perform and analyse stochastic sheet metal forming simulations.
- The TriboForm friction model, which is an advanced model that can accurately predict the tribology conditions in a sheet metal forming process.
- Cold Forming with Temperature Effects, which can perform thermo-mechanical simulations and predict the results after a given number of parts or at steady state conditions.

2.2 Volvo XC60 Wheel House Outer

Figure 1 shows the part design and D-20 stamping process design. This is a double attached part, i.e. left hand and right hand Wheel House Outer is produced in the same part. The material is CR4 according to VDA329-100, [15], and the sheet thickness is 0.6 mm. From the start of production, three different tribological systems, i.e. combinations of sheet coatings and pre-lubricants have been used:

- At the start of production, the coating was G150/50-U and the pre-lubricant was Fuchs Anticorit RP4107S, $1.0 \pm 0.5\ g/m^2$. This combination gave a very unstable production with frequent necking and fracture problems. An example of a fractured part is shown in Figure 2. This tribological system is included in the study and is referred to as RP4107S.
- Based on the successful results from trials with ZM coating at Volvo Cars, the coating was changed to ZM35/35-U and the same type and amount of pre-lubricant. This modification solved the stamping problem but generated a welding problem in the body shop. Since this was an intermediate solution, this lubrication system is not included in the current study. But the same simulations that was performed in this study can also be performed for this tribological system.
- The coating was then changed back to GI50/50-U but the pre-lubricant was changed to Fuchs Anticorit PLS100T, $0.8 \pm 0.3\ g/m^2$. This combination also solved the stamping problems and did not generated any problems at other parts of the car plant. This is the combination still used today and also this tribological system is included in the study and is referred to as PLS100T.

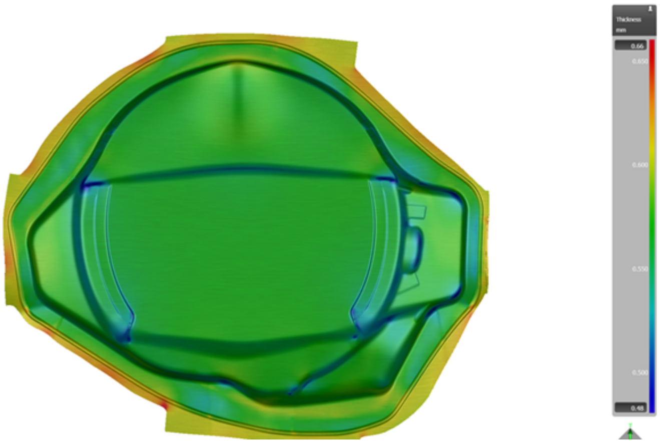
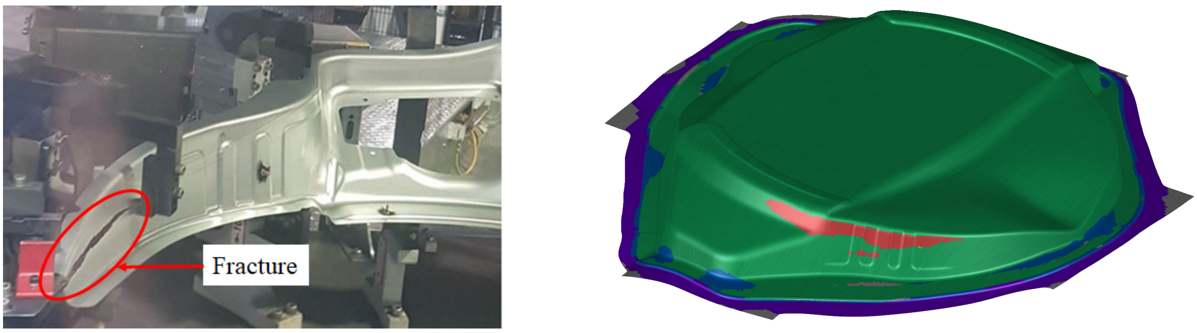


Figure 1: Wheel House Outers for Volvo XC60. The image shows thickness distribution after forming and the range is from 0.48 to 0.66 mm.

2.3 FE-simulation model set-up

The D-20 forming operation is simulated as a double action drawing operation with AutoForm R12. The ram velocity profile is assumed to be sinusoidal and the stroke rate is set to 10 strokes per minute. Since the part is stamped in a double action drawing operation, the used blank holder force in production is unknown. This study is therefore focusing on predicting the maximum blankholder force at onset of necking as function of lubrication amount, number of produced parts and variation of sheet material properties for each tribological system. The assumption is that the blank holder is completely closed with cold dies at the start of production. For each produced part more and more heat is generated and transferred into the die surfaces until a steady state condition is reached. This will lead to thermal expansion of the die surfaces and in the blankholderarea this will then increase the restraining of the sheet since the gap is decreasing. The hypothesis is therefore that a tribological system with a low maximum blankholder force at onset of necking is more probable to generate failed parts than a system with a very high maximum blankholder force at onset of necking.



(a) (b)

Figure 2: Example of a fractured Wheel House Outer from Volvo Cars Body Shop is displayed to the left (2a) and results from a simulation using a very high blank holder force is displayed to the right (2b).

The hardening curve and used Forming Limit Curve (FLC) are displayed in Figure 3. The hardening curves are displayed in the left figure and note that material has positive strain rate effect. The FLC is displayed to the right and is the curve for onset of necking. The used yield loci in the study is the BBC2005 material model with the parameters presented in Table 1. See [12]-[13] for a detailed description of BBC2005.

Data from the TriboForm models of the two tribological systems are displayed in Figure 4. The figure to the left show the coefficient of friction as a function of contact pressure and temperatrure

Material	σ_0/σ_0	σ_{45}/σ_0	σ_{90}/σ_0	σ_{bi}/σ_0	r_0	r_{45}	r_{90}	r_{avg}	r_{bi}	M
CR4	1.0000	1.0370	0.9951	1.149	2.219	1.702	2.496	2.030	1.000	5.3

Table 1: Input data for the BBC 2005 material model

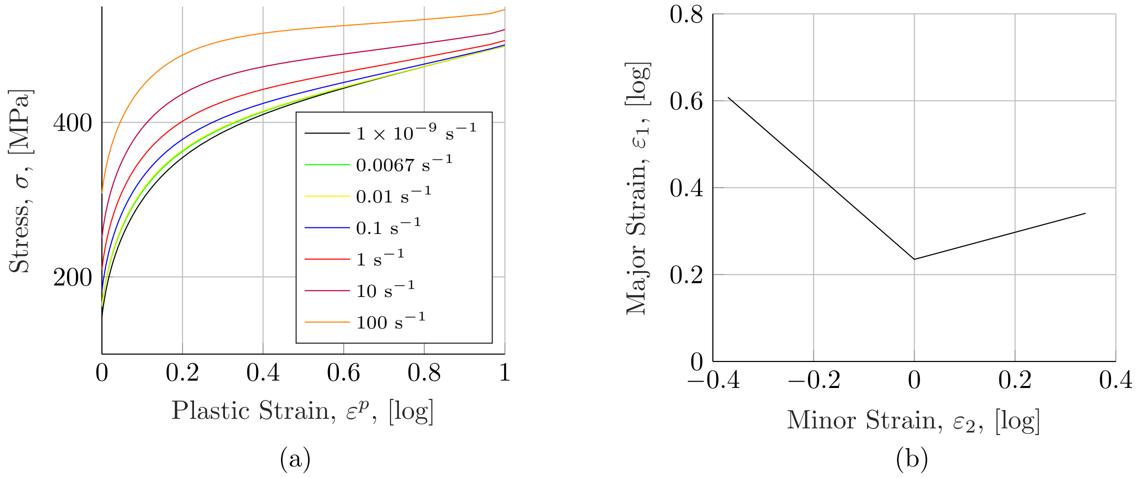


Figure 3: The hardening curves at different strain rates are displayed to the left are (3a) and the FLC at onset of necking is displayed to the right (3b).

for the two systems. The figure to the right shows the temperature dependency for the two models at different relative velocities at a midsurface effective plastic strain of 0.1 and a contact pressure of 20 MPa. These figures reveals some interesting observations. Both tribological systems have a strong pressure dependency, i.e. with increasing contact pressure the coefficient of friction is decreasing. Both systems has a similar dependency, but the PLS100T has always lower values compared to RP4107S. The temperature dependency is more complex. It depends also on other parameters, e.g. midsurface effective plastic strain, relative sliding velocity and contact pressure. For a low relative sliding velocity, in this case 10 mm/s, the temperature dependency is low for both systems. But for a high relative velocity, in this case 200 mm/s, the RP4107S system has a strong temperature dependency at lower temperatures. At higher temperatures, the coefficient of friction is independent of temperature for RP4107S. For the PLS100T system, the influence of temperature is small also at low temperatures.

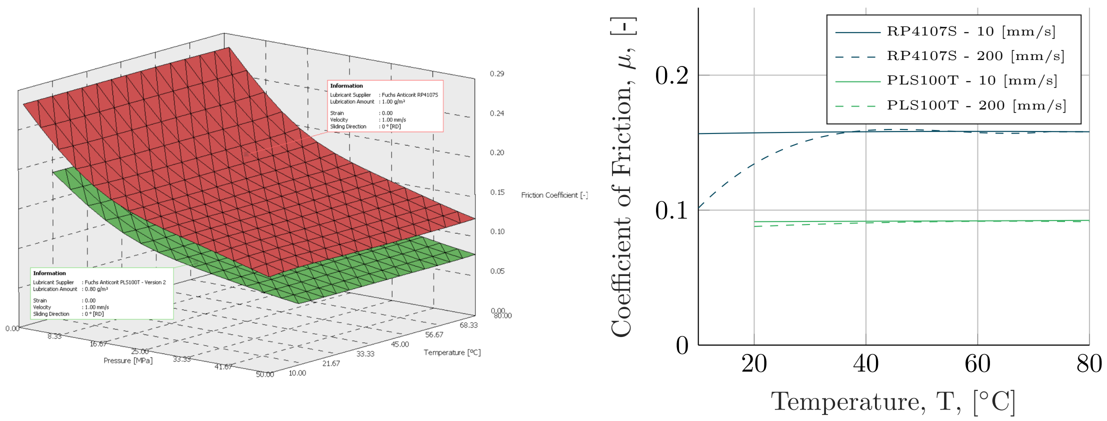
The thermal properties used for Cold Forming with Temperature Effects are all AutoForm default values, except the Heat Transfer Coefficient between sheet and tool that is set to 7.0 mW/mm^2K based on the results in [14].

	R_p [MPa]			R_m [MPa]			r_{avg} [-]		
	Min	Nominal	Max	Min	Nominal	Max	Min	Nominal	Max
Full range	140.0	147.9	180.0	270.0	290.7	330.0	1.60	2.03	2.40
Reduced range	140.0	147.9	159.9	283.9	290.7	297.5	1.93	2.03	2.40

Table 2: The used material variation in the study

Each AutoForm Sigma simulation consists of 80 realisations. The AutoForm Issue used for evaluation is using Max Failure (Advanced) with a Limit Value of 1 and Warning Value of 0.99. This gives a distinct transition between OK parts and NOK parts. For each tribological system, three different Sigma models are simulated, representing the results for part 2, part 1000 and part 2000. The current implementation in AutoForm request that the simulation should be repeated in order to be able to do a Sigma evaluation. Therefore, part 2 is our reference for start of production. Part 1000 is representing the condition in a middle of batch and part 2000 represents the final part of the batch.

Table 2 presents the ranges for the material properties in this study. The set-up of the model is using the values in the row Full Range. These values are the same as the limits for CR4 in VDA239-100, with



(a) (b)

Figure 4: The coefficient of friction for the two tribological systems in the study. To the left the coefficient as a function of contact pressure and temperature is displayed (4a) and to the right the coefficient of friction as function of temperature for two different sliding velocities is displayed (4b). The RP4107S system is the red surface and curves and the PLS100T system is the green surface and curves.

the exception that in VDA239-100 there is no upper limit for the r_{avg}. The intension with this set up is to determine the limit blankholder force for all possible types of CR4 materials from different suppliers. The row Reduced range represents expected variations today when a part is produced with material for just one supplier. All material properties are regarded as Uncontrollable parameters and the correlation between R_p and R_m is 85%.

The blankholder force and the lubrication amount are regarded as Controllable parameters. The blankholder force in each model are presented in Table 3. The motivation for these blankholder force values in each simulation is that there should always be OK parts for all combinations of lubrication amount, blank holder force and variation of mechanical properties in each simulation. Therefore the nominal blankholder force should generate an OK part, the minimum blankholder force should results is a green lower left corner in Figure 5 for the full range of material variation and the maximum blankholder force is set so that the upper left corner in Figure 5 is either yellow or red with reduced range of material variation.

	RP4107S		PLS100T	
	Part 2	Part 1000 and 2000	Part 2	Part 1000 and 2000
Minimum	900	900	1550	1550
Nominal	925	925	1600	1590
Maximum	1030	1000	1750	1750

Table 3: Cushion force i kN in the different simulations

For the RP4107S system, the nominal lubrication amount is 1.5 g/m^2, the minimum amount is 0.5 g/m^2 and the maximum amount is 3.0 g/m^2. The corresponding value for the PLS100T system is a nominal lubrication amount of 1.3 g/m^2, a minimum amount of 0.8 g/m^2 and a maximum amount of 1.8 g/m^2. The motivation for these ranges is that RP4107S is only a rust protection lubricant with a low viscosity and it is also known to have a large migration of the lubricant during transport and storage. PLS100T is 2^{nd} generation stamping lubricant with high viscosity and low migration and as was seen in Figure 4, the coefficient of friction for this system is always lower than for RP4107S even if the amount of lubricant is lower.

3 Results

3.1 Introduction

Each Sigma simulation is analysed in the following way. In Trial mode, lubrication amount and blankholder force are manually modified in order to find the limiting values for onset of an NOK part for different

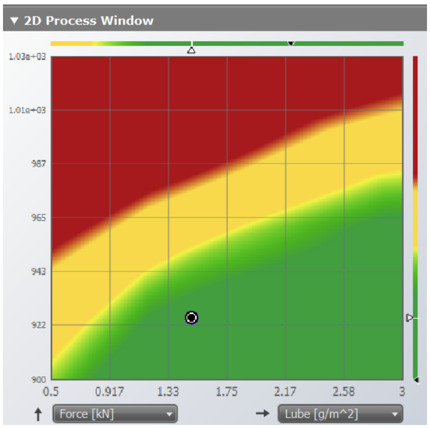


Figure 5: An example of a 2D Process Window

combinations of blankholder force and lubrication amount. This creates a curve and this curve is the same as the border curve between green and yellow areas in Figure 5. This procedure is performed with both the full range and the reduced range of material scatter. Also the punch force at all limit values of lubrication amount and blankholder force is documented.

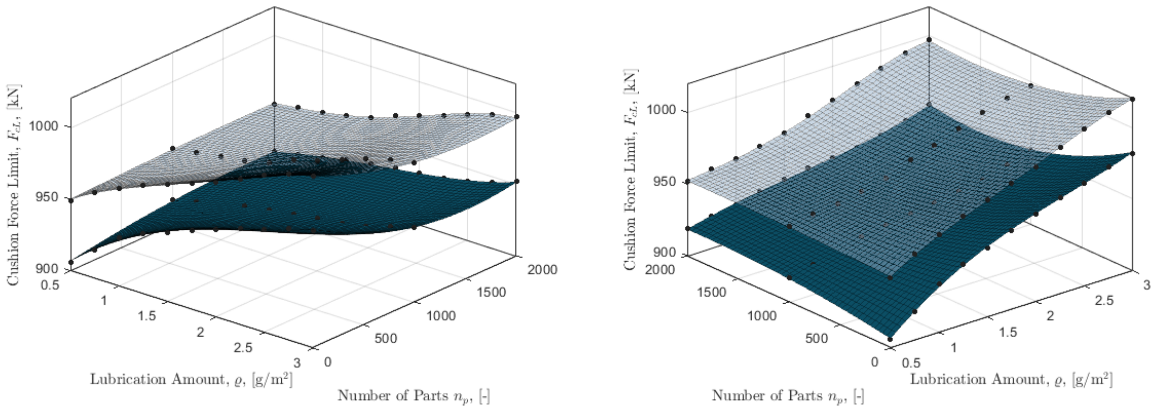


Figure 6: Maximum blankholder force for RP4107S as a function of lubrication amount and number of produced parts. The dark surface are the values for the full material variation and the light surface is for the reduced material variation. The points are the determined values from analyses of the AutoForm Sigma models.

3.2 Max blankholder force for RP4107S

Figure 6 shows the maximum blankholder force as a function lubrication amount and number of produced part for the RP4107S system. For the full range of material variation, the dark coloured surface, an increase of the lubrication amount increases the maximum blankholder force independent of number of produced parts. But for the first parts, the increase is much larger at part 2 than a part 1000 and 2000. At low lubrication amounts, the limit blank holder force is actually increasing with number of produced parts which is slightly unexpected. But with this highly non-linear model it is impossible to make intuitive conclusions of the behaviour. At higher lubrication amounts, the limiting blankholder force is decreasing with increasing number of produced parts. However, the difference between part 1000 and part 2000 is negligible. With a reduced range of the material variation, the light coloured surface, the maximum blankholder force is increasing slightly compared to the full range and the shape of two surfaces are similar.

3.3 Max blankholder force for PLS100T

Figure 7 shows the maximum blankholder force as a function lubrication amount and number of produced part for the PLS100T system. For the full range of material scatter, the dark coloured surface, the surface has a more complex shape which is surprising given that Figure 4 showed a very limited temperature dependency for this system. It is probable that the highly non-linear nature of the model also explain these results. One interesting observation is that for high lubrication amounts, the maximum blankholder force is strongly decreasing with increasing number of parts. At lower lubrication amounts, the maximum blankholder force is almost independent of the number of produced parts. For the reduced range of the material variation, the light coloured surface, the shape of the surface is also complex and different from the surface for the full range. Up to 1.2 g/m^2 of lubrication, the maximum blankholder force is increasing with increasing lubrication amount. Increasing the lubrication amount will then first reduce and then increase the maximum blankholder force until the amount is 1.8 g/m^2. For that amount, the limiting blankholder force is at the same level as for 1.2 g/m^2. This has the implication that there is an upper limit for the optimum amount of lubrication and exceeding this limit will reduce the maximum blankholder force. In general, the number of produced parts has a little influence on when the maximum blankholder force for the reduced range of material properties.

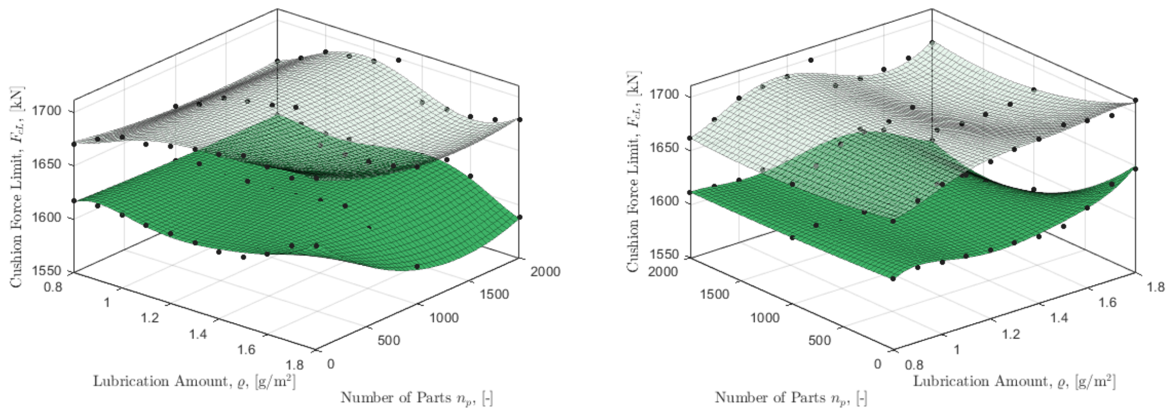


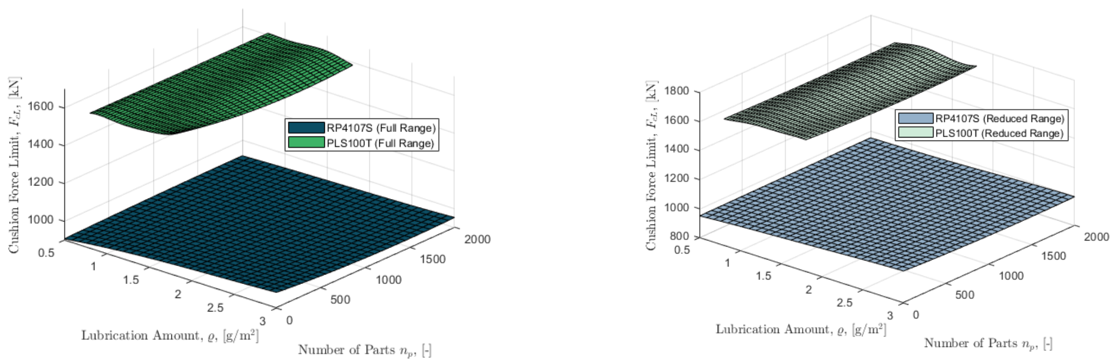
Figure 7: Maximum blankholder force for PLS100T as a function of lubrication amount and number of produced parts. The dark surface are the values for the full material variation and the light surface are the values for reduced material variation. The points are the determined values from analyses of the Sigma models.

3.4 Comparison of maximum blankholder force for the two tribological systems

Figure 8 displays the results in Figure 6 and Figure 7 simultaneously, so a comparison of the results for the two systems can be made more easily. For both a full and reduced range of material scatter the maximum blankholder force is almost twice as high for PLS100T compared to RP4107S. This an interesting observation and it implies that the forming window is much larger for PLS100T than for RP4107S. This conclusion is also supported by the observations in production described in Section 2.2.

3.5 Sheet and tool temperatures using the two tribological systems

Figure 9 displays maximum sheet and tool surface temperatures as a function of the number of produced parts for the two tribological systems. Using RP4107S, the temperatures in both the sheet, blankholde and die surfaces is continuously increasing with increasing number of produced parts. For the sheet and all stamping die surfaces using PLS100T and the punch surface using RP4107S, the temperatures are constant after 1000 produced parts. The temperature of the sheet is also slightly lower using PLS100T than using RP4107S. These results are to some extent expected since PLS100T is more advanced lubricant than RP4107S and this should result in lower temperatures and that a steady state situation is reached after a lower of number of parts for compared to PLS100T.



(a) (b)

Figure 8: The maximum blankholder force as a function lubrication amount and number of produced parts for the two tribology systems displayed together. To the left the results for the two systems and a full range of material scatter (8a). The right results for the two systems and a reduced range of material scatter (8b).

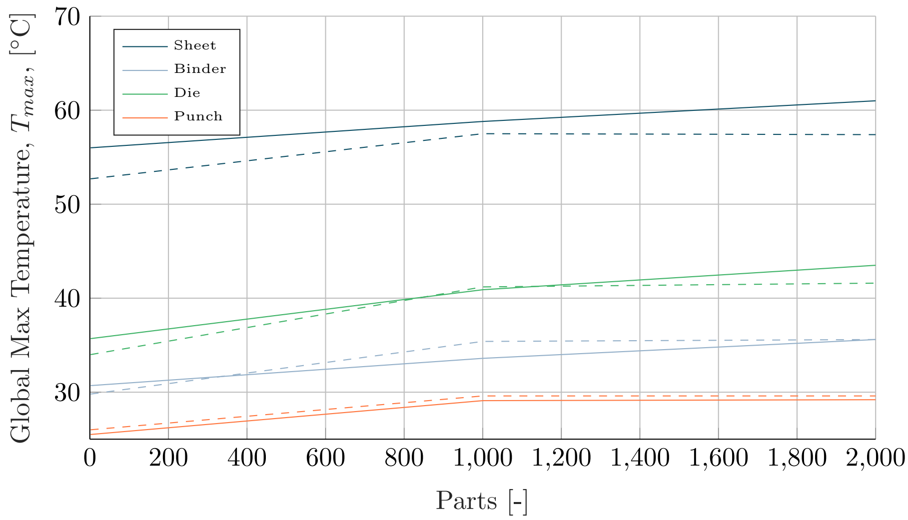
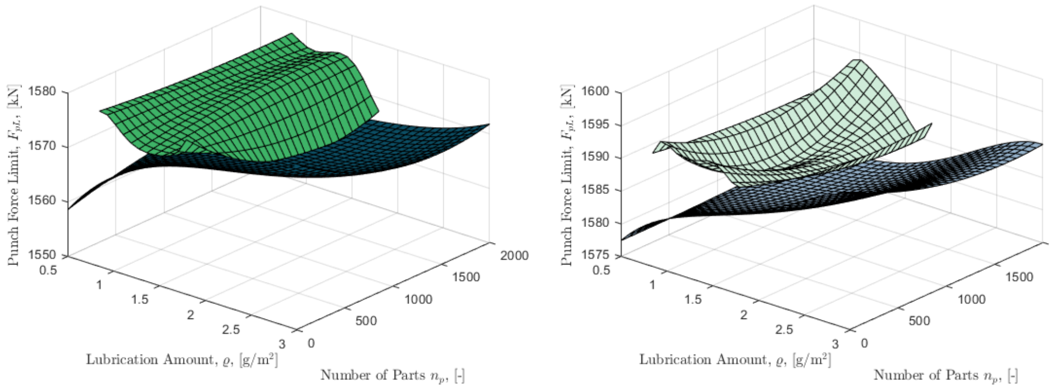


Figure 9: Numerically predicted global maximum temperatures of the sheet and tools. The solid lines represent the RP4107S lubrication system, while the dashed lines represent the PLS100T lubrication system.



(a) (b)

Figure 10: Punch force at maximum blankholder force as a function of lubrication amount and number of produced parts for the two tribology systems. To the left the results for the two systems and a full range of material scatter (10a). To the right results for the two systems and a reduced range of material scatter (10b).The blue surfaces are the force using RP4107S and the green surfaces are the force using PLS100T.

3.6 Punch force at maximum blankholder force for the two tribological systems

Figure10 displays the punch force at maximum blankholder force as a function of lubrication amount and number of produced parts for the two lubrication systems and for both a full and a reduced range of material scatter. All four surfaces has a very complex shape and it is very hard to draw any general conclusions about the influence of lubrication amounts, number of parts and the range of the material scatter. But all four surfaces have almost the same values which is a an interesting observation given the large difference in maximum blankholder force for the two tribology systems. This observation opens up for a possibility to monitor and control the stamping process by measuring the punch force.

4 Conclusions and discussion

There are several conclusions that can be drawn from all the presented results from this study. The first conclusion is the importance to have a good tribological system in the stamping process. By just changing the lubricant, the maximum blankholder force is almost doubled for the studied part. Using RP4107S the maximum blankholder force is in the range of 900-1000 kN and compared to the required force to close the blankholder which is in the range of 650-700 kN, the forming window is not that large. For PLS100T the maximum blankholder force is in the range of 1600-1700 kN which is more than twice the required force for closing the blankholder and this gives a large forming window.

The second conclusion is that even if a tribological system has a limited temperature dependency, the effects over the production of a complete batch can be noticeable. The PLS100T system has a very little temperature effect but the results shows for example that there is an upper limit for the applied amount of lubricant, for this part 1.2 g/m^2 using a reduced range of material scatter. If more lubricant is added, the maximum blankholder force is actually decreasing. This value is the total amount of lubricant in the stamping process and if one assumes that 0.2-0.3 g/m^2 is remaining in the die after stamping of each part, the applied amount on the blank at the supplier should be approximately 1.0 g/m^2. This is not far from the values current used at Volvo Cars for this lubricant which is normally 0.8 g/m^2.

The results also shows the range of the material scatter influences the maximum blankholder force. An increased material scatter reduces the maximum blankholder force. The results also shows that for both tribological systems, an increased lubrication amount cannot fully compensate for the reduction of maximum blankholder force due to increased material scatter.

The fact that the punch force for all systems and ranges of material scatter is similar opens up a possibility to monitor and control the stamping process by measuring the punch force. In case of a double action process, monitoring is the only option since the process is controlled by the position of the outer ram. But measuring the punch force could give important information that can support the personal at the press line and alert them that a part has failed. For a single action process, in theory the punch force could also be used to control the stamping process but more research is needed to develop such a technology.

This study shows examples of the type of results and conclusions that can be determined by combining AutoForm Sigma, TriboForm friction models and performing thermo-mechanical simulation by using the feature Cold Forming with Temperature Effects. Performing more simulation representing the situation at different number of produced part will refine the limiting surfaces. For example, is it possible to determine the number of part when the process has reached a steady state by iterating the simulations. The methodology used in this study can also be applied when the effects of a change of material supplier or material grade should be evaluated. This will be a very useful tool when more environmentally sustainable sheet materials will be introduced in production in the future.

Acknowledgement
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