Introductory study of sheet metal forming simulations to evaluate process robustness

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Abstract. The ability to control quality of a part is gaining increased importance with desires to achieve zero-defect manufacturing. Two significant factors affecting process robustness in production of deep drawn automotive parts are variations in material properties of the blanks and the tribology conditions of the process. It is imperative to understand how these factors influence the forming process in order to control the quality of a formed part. This paper presents a preliminary investigation on the front door inner of a Volvo XC90 using a simulation-based approach. The simulations investigate how variation of material and lubrication properties affect the numerical predictions of part quality. To create a realistic lubrication profile in simulations, data of pre-lube lubrication amount, which is measured from the blanking line, is used. Friction models with localized friction conditions are created using TriboForm and is incorporated into the simulations. Finally, the Autoform-Sigmaplus software module is used to create and vary parameters related to material and lubrication properties within a user defined range. On comparing and analysing the numerical investigation results, it is observed that a correlation between the lubrication profile and the predicted part quality exists. However, variation in material properties seems to have a low influence on the predicted part quality. The paper concludes by discussing the relevance of such investigations for improved part quality and proposing suggestions for future work.

1. Introduction

Sheet Metal Forming (SMF) is the process of transforming a piece of sheet metal into a desired shape [1]. During this process, a metal sheet called blank, is placed between a die and a blankholder that holds the blank with the correct amount of pressure. A punch then plastically deforms the blank to attain the desired shape. SMF is a complex process involving several non-linearities and other phenomena such as elastic deformation of dies, temperature variation of tools and varying tribology conditions [2,3]. One major concern during SMF is the quality of produced parts. Issues with quality can be recognized in diverse ways such as necking, fractures, surface defects, wrinkles and violation of geometric specifications due to excessive springback. Such issues incur increased costs, delays, resource wastage and reduce the overall production efficiency. To be able to control the quality of a part, it is important to understand the influence of various parameters affecting quality both directly and indirectly.

Present work aims to examine the influence of material and tribology conditions on the prediction of part quality via numerical simulations. It is an initial step aimed towards achieving quality control...
within an Industry 4.0 framework. Industry 4.0 essentially means using data collected in real-time to integrate and improve manufacturing process [4]. Model-based control systems combined with knowledge about how product behaves under various conditions has a potential in improving product quality [4]. Simulation models with reliable and validated prediction accuracy could improve knowledge about the system behaviour as well as support in creating mathematical models representing the system. These mathematical models could then guide control algorithms in real-time to decide upon the optimum product properties and tool settings that should be adopted for improved quality of parts.

2. Research problem and approach

2.1. The problem
The part considered for this research is a front door inner panel of a Volvo XC 90 as shown in figure 1 (left) [5]. This part is produced in five manufacturing steps involving drawing, trimming, flanging and restriking operations. Only the major forming step that involves drawing operation is considered for this study since it is assumed to affect the part quality the most.

![Figure 1. Front door inner of a Volvo XC 90 (left) and regions in production with quality issues like fractures (dashed lines) and wrinkles (solid lines) (right).](image)

Depending on varying conditions like stroke rate, cushion force or friction, it has been observed that wrinkles and fractures occur on this part resulting in instances where the formed part does not match geometric specifications. In addition, these issues tend to vary after a number of parts are produced and is suspected to be due to changing process conditions such as tooling temperature, sliding velocity between blank and die interfaces. Figure 1 (right) shows some regions with quality issues in production. Such issues are highly undesirable and decrease the overall production stability [3]. Volvo Cars has been actively doing research [6,7] to detect, understand and solve forming problems. This work builds on this previously conducted research.

2.2. The approach
With the ultimate goal to control quality of a produced part, the present work aims to attain a preliminary understanding of the influence of material and lubrication properties (section 3.2.3) on the numerical predictions of part quality through SMF simulations. The first step towards this is to build a simulation model that could reliably account for production conditions, such as elastic press and die deformations and tribology system. The results from this simulation model can be compared with the measurements of the formed part in reality to validate the prediction accuracy of the model. Once a reliable simulation model is accomplished, influence of material properties and lubrication conditions can be investigated using the AutoForm-SigmaPlus [8] software module. This software module allows direct investigation of the influence of product properties by defining them as design variables and running multiple simulations while varying these design variables within stated quality targets. In addition, it is also possible to explore what-if scenarios by parametrically adjusting design variable values and studying how the model behaves in such situations. Finally, the simulation results and the observations from the production facility could be compared to improve knowledge and identify trends.
3. Model Description

3.1. Production system
The part considered for this study is produced in a single action transfer press. The Material of the die is Cast Iron, GGG70L. The die and punch are chrome plated in some regions according to Volvo Cars recommendations. The blankholder surfaces are laser hardened and polished. The blank material is VDA239-CR4 with Galvanised Iron (GI) coating. The blank is 0.7 mm thick with Fuchs Anticorit RP41075 prelubrication. Data from the press, die and blank such as velocity profile of the press, scanned data of the die forming surfaces (section 3.2.1) and the lubrication amount across the blank (section 3.2.2) are recorded for use in forming simulations.

3.2. SMF simulation setup
All forming simulations are carried out in AutoForm plusR7 software. The process forming tools, curves/points to define blank outlines and the trim sections for defining trimming profile are imported into AutoForm from the Volvo Cars database. Material model BBC2005 [9] is used for the blank material in all simulations. Details about the experimental measurements, the hardening model and corresponding parameters used in the material model can be found in [9]. All simulations use an inbuilt blankholder model with support type Force Controlled and loading condition Columns. These settings allow mimicking real press conditions.

3.2.1. Including other SMF phenomena into simulations.
To save computational resources, most commercial forming simulation software, including AutoForm, represent large 3D die structures as 2D rigid surfaces. Hence the press and die structures are assumed to be rigid in most industrial SMF simulations although these structures deform in reality [7]. Previous research [7,10] has demonstrated improvement in prediction accuracy by accurately accounting for press and die deformations in forming simulations. This paper has implemented the procedure presented in [7] to account for elastic press and die deformations within forming simulations. Figure 2 (left) shows the distance between the blankholder and die in z-direction when undeformed. This plot is created using Atos/GOM software in which the scanned surfaces of the blankholder and die are positioned such that the closest distance between them is 0.7 mm. This distance is equal to the blank thickness and is the gap expected between the blankholder and die in reality, just before the forming process has begun. However, as seen in figure 2 (left) many regions have a gap of almost double the sheet thickness which is due to manual reworking of the die surfaces before they are installed into the press. These gaps become uniform and equal to sheet thickness when the die is installed into the press due to elastic press and die deformations and not accounting for these deformations in the simulation models could render less prediction accuracy. Hence, a structural FE-model of the die and blankholder is built in Hypermesh using their CAD geometrical models. The surfaces of these CAD models are replaced with the scanned surfaces of the original blankholder/die and then solved in Abaqus. The result from the structural analysis produces die and blankholder deformations similar to that in reality with a uniform gap of about 0.7 mm as shown in figure 2 (middle). These deformations are then transferred from 3D structures in Abaqus to 2D surfaces in AutoForm using sub-modelling. The deformed 2D surfaces are then used for forming simulations. For a detailed account of the followed procedure, the reader is referred to Pilthammar et al. [7].

Previous research [6,11] has demonstrated a strong influence of tribology conditions on part quality and an improvement in prediction accuracy by precisely accounting for tribological conditions. Research [6] at Volvo Cars presents an approach to accurately represent complex tribological phenomenon using TriboForm. TriboForm is a software that allows the user to numerically model and simulate interactions between sheet material, lubricants, process tools and coating materials [12]. The approach adopted in this work is based on the procedure proposed in [6]. A numerical model is built using information about process conditions and the involved tribology system. The TriboForm Analyser module is used to perform friction analysis in which, friction coefficients are calculated for a predefined range of process parameters such as relative sliding velocity between blank and die interface, local contact pressure, plastic strains in the sheet material and interface temperatures [12].
The result from this analysis generates friction coefficient data points and is stored as a friction file. Figure 2 (right) shows a 3D plot of the generated friction file having two surfaces. One surface represents friction conditions for a combination of GI coating with laser hardening while the other surface represents for a combination of GI coating with chrome plating. These surfaces represent friction coefficient values for corresponding local contact pressure, relative sliding velocity and coating material. With the TriboForm FEM Plug-in, it is possible to integrate and use the generated friction file in the AutoForm software. This enables the allocation of dynamic friction coefficients during the forming simulation.

![Figure 2](image_url)

**Figure 2.** Distance between blankholder and die in z-direction when undeformed (left) and when deformed (middle), 3D plot of the simulated friction behaviour (right).

### 3.2.2. Including in-line measurement data into simulations.

An equipment to measure and monitor the amount of lubricant on the blank is installed in one blanking line at Volvo Cars which stores all measured data on a central server. This data is available to visualize both on site at the blanking line and offline. It is observed that the blank has a varying lubricant distribution along its length/width with lubricant amounts varying between 0.6 g/m² to 2.3 g/m². To mimic the lubrication distribution observed in reality, CAD geometry of the blank outline is divided into several sections by adding lines in Catia V5. Using the sectioned blank outline, a tailor welded blank with uniform thickness and material properties but varying lubrication amounts is then generated within the forming simulation software.

![Figure 3](image_url)

**Figure 3.** Typical variation of lubrication along the length and width of the blank (left) and division of the blank in CAD based on lubrication data (right).

Figure 3 shows the variation of lubricant along the length and width of the blank (left) and how the blank is divided into sections based on pre-lube measurement data (right). The benefit of this approach is twofold: Firstly, it allows to create a more realistic lubricant profile by making it feasible to assign individual lubricant amounts to each section (average lubricant amounts are assigned to each section in this case). Secondly, it enables to build a more robust Sigma setup by offering the possibility to vary lubricant amount in each section separately (section 3.2.3). After incorporating all above-mentioned phenomena into the model, it is run in the forming simulation software and validated (section 4.1) to verify the model’s prediction accuracy before proceeding to the numerical investigations.
3.2.3. Numerical investigations

AutoForm-Sigmaplus is a software module dedicated for improving the robustness of SMF process/products and is fully integrated with AutoForm’s work environment [8]. It allows to define and vary a set of design variables within user-defined ranges and evaluate system behaviour under different values of these design variables. For example, in a usual simulation setup within AutoForm, a single value for blankholder force (nominal value) is specified. Using the Sigma module, it is possible to specify the range between which the force value can vary, that is, the upper and lower limits for the blankholder force. Based on the entered nominal value and range, the Sigma module automatically discretizes the range into a number of sample points and assigns values to these points for Sigma analysis based on a Latin hypercube approach [8]. This results in a set of points varying between the defined range for that design variable. A similar procedure is used to calculate the set of points for all design variables. The Sigma module also allows to define dependency amongst various design variables. For example, in the present work, the blankholder force is applied through a column loading condition with the load equally distributed between two columns. It is necessary to define the dependency between both column loads for them to vary simultaneously. This is done by defining one of the variables as a Master, that is, as an independent design variable and the other as dependent on the Master variable. Such dependencies can be specified for all design parameters. A benefit with defining dependencies is that the number of independent variables amongst all design variables is reduced as is the number of simulations required for the Sigma analysis as explained further. The next step is to define the number of simulations required for carrying out the Sigma analysis. This can be done in two ways; one way is to use the default setting, Automatic, in case of which, the software recommends a value for the required simulations based on the number of independent Sigma variables defined. Another way is to manually input the desired number of simulations, with the least possible number of simulations being 12. The created set of points is used to vary the value of design variables during different simulations. Using the procedure detailed so far, two unique Sigma configurations with different variables are created and its main characteristics are summarized in table 1.

| Configurations | Design variables | Material coating | Material Scatter | No. of sections | Blankholder Force (Tonne) Nominal | Range | Lubricant (g/m²) Nominal | Range |
|----------------|------------------|------------------|-----------------|----------------|----------------------------------|-------|------------------------|-------|
| Config 1       | GI               | Yes              | 1               | 150            | 130-300                          | 2.0   | 1.0-3.0                |       |
| Config 2       | GI               | No               | 5               | 150            | 130-300                          | 1.0   | 1.0-2.0                | 1.5   | 1.5-2.5               | 2.0   | 2.0-3.0               |

Configuration 1 intends to investigate the effect of material property variation on the quality of the part. For this purpose, three independent material variables namely, Lankford coefficient (R), Tensile stress (Rm) and yield stress (Rp0.2) are created. A preliminary analysis of the raw data from material tests is conducted to identify the upper and lower limit values for the created material variables. Then the range within which these material variables should vary are entered based on which the Sigma module automatically creates the sample points for Sigma analysis using the procedure mentioned earlier. Two other design variables namely, blankholder force and lubricant amount are also created to examine whether variations of these variables have a higher influence than variation in material variables. In this case, the blank is not divided into any sections since the purpose with lubricant variation is only to see whether it has a higher influence than material property variation.

Configuration 2 intends to investigate the effect of lubrication amount variation on part quality. To be able to incorporate a realistic lubrication profile, the blank is divided into 5 sections using the strategy outlined in section 3.2.2. Then, unique lubrication variables are created for each section. Lubrication variable for 1 of the sections is defined as master and the remaining variables are defined as dependent on the master with a positive dependency. This allows variation of the lubricant amount...
for the entire lubrication profile simultaneously without disturbing the profile shape. Since the SigmaPlus module in AutoFormPlus R7 doesn’t allow assigning lubricant value less than 1 g/m², the starting value for all lubrication amount ranges is defined as 1 g/m² and is varied discretely as per calculated sample point values (section 3.2.3). A blankholder force variable is also created to be able to visualize the effect of lubrication variation at different blankholder forces. All other settings of the Sigma model are similar to the initial simulation model (section 3.2). All Sigma models are run on Volvo Cars remote server with the respective number of simulations for configuration 1 and 2 being 80, 32. The element type used is triangular elastic plastic shell elements with an initial mesh size of 20mm and 5 integration points over the sheet thickness.

4. Results and Discussions

4.1. Validation
A common approach to validate the prediction accuracy of the simulation model is to compare the strain measurements from a real part with the strain predictions from simulation results. Since it was not possible to conduct strain measurements on the real part, the second-best option is to compare the thickness of the formed part with the thickness from simulation results. Thickness measurements on the real part were conducted in 50 points using a high-precision ultrasonic measurement device. Figure 4 (left) shows the material thickness from the measurements (only few points) and from the simulation results. On comparison, it is noticed that the difference between both results lie in the range of 2% to 5%. This implies that on average, both measurements differ by 3.5 % which depicts that the result correlates quite good and that the prediction accuracy of our simulation model is satisfactory.

4.2. Influence of material properties and lubrication amounts
One way to visualize the influence of varying material properties and lubrication amounts is by observing the variation in major strain. Major strain is the value of strain corresponding to the major deformation axis. A variation in major strain result at a particular point depicts the difference between the maximum and minimum major strain value from the Sigma simulation. An increase in major strain value beyond the forming limit curve for necking indicates that the part has failed. A higher variation in major strain due to variation of a Sigma variable indicates a higher probability of failure in that region of the part. In addition this also indicates a larger influence of that Sigma variable on the predicted part quality. Figure 4 (right) shows the variation in major strain due to variation of material properties (that is variation of R, Rm and Rp0.2). It is observed that variation of these material properties has very low influence on the variation of major strain for the considered part geometry.

![Figure 4](image_url)

Figure 4. Comparison of measured (marked points) vs predicted material thickness (left) and variation in major strain due to variation of material properties from simulation results in absolute scale (right).

Figure 5 shows the plot of major strain variation due to all sigma variables for configuration 1 (left) and 2 (right) with 1 and 5 blank sections respectively. Configuration 1 has an additional sigma variable for material property variation which has minor influence on the major strain variation as already seen in figure 4 (right). As seen in table 1, the lubrication range in the marked region of figure
5 varies from 1-3 g/m² for configuration 1 whereas from 2-3 g/m² for configuration 2. Even though the lubrication variation of configuration 2 is less than that of configuration 1, configuration 2 shows a higher variation in major strain than 1. In other words, the marked areas in figure 5 predicts a larger variation in major strain for blank with 5 sections than for blank with 1 section. It is also observed that the maximum value of major strain is higher for configuration 2 than for 1. This expresses that depending on how the lubrication profile is modelled, the simulation produces different predictions.

![Figure 5. Variation of major strain for blank with 1 section (left) and 5 sections (right).](image)

![Figure 6. Formability plot at maximum blankholder force for blank with 1 section (left) and blank with 5 sections (right).](image)

During SMF, on increasing the blankholder force, the blank is held more tightly due to increased restraining force. At a certain value of blankholder force, this restricts the flow of material to an extent that results in fracture due to excessive thinning. To examine whether the simulation results depict a similar trend, the formability result from Sigma analysis at maximum blankholder force for blank with 1 and 5 sections is examined as shown in figure 6, left and right, respectively. The Formability result gives a quick survey of the parts ability to form into the desired shape based on the computed results considering the strain state in forming limit diagram. The marked area in figure 6 predicts a risk of splits in the case of blank with 5 section (right) while no risk of splits in the case of blank with 1 section (left). This indicates a difference in predictions when modelling lubrication profile in different ways.

5. Conclusions
This research is an initial step towards achieving quality control of parts manufactured in production. The current need is a shift in the trend from solely controlling production tool parameters to controlling product properties and process conditions. The present research demonstrates a procedure to investigate the effects due to variation of design parameters on the simulation results using a commercial forming simulation software. The material and lubrication properties are varied over a certain range and the effects due to this variation are visualized and compared to gain a preliminary understanding of the effect of these parameters on the numerical predictions of part quality. Results indicate a correlation between numerical predictions of the part quality and the part lubrication. Depending on how the lubrication profile is modelled, some regions in the part exhibit different variations in major strain and formability results. The suggested way to model lubrication is to use pre-lube measurement data from the production line. The approach for including phenomena such as elastic press and die deformations, modelling realistic friction conditions and building lubrication profile using pre-lube data is also briefly discussed. It must be noted that all conclusions stated are valid only for this study, that is, for the part, lubricant and coatings used in this work. More investigations on several car parts are needed in order to generalize and gain a deeper understanding of these results. From a broader perspective, more of such investigations would improve knowledge about what affects part quality and how issues with quality can be solved. This could potentially improve the quality of manufactured parts, reduce the time spent on identifying and solving quality issues by providing improved decision support. In future, such investigations could provide the capability to predict the required product /process conditions in order to meet desired quality targets.
6. Future work

Future research will involve a more detailed investigation. Some ways to take this research forward could be as follows: Firstly, strain measurements from the real part should be compared with measurements from simulation results to verify the accuracy of this model in detail. The present research considers lubricant distribution only on one side of the blank since only single side measurements were available. However, the blank in reality has lubricant present on both sides. Next steps could be to model lubricant distributions of both sides when lubricant measurements from both sides are available. Processing lubricant data consumes time and resources. Future research could aim at building an automated pre-lube data processing strategy with as many pre-processing tasks automated as possible. The forming process involves large loads over varying frictional conditions. This results in temperature rise of the process tools even in a cold forming setup. Future research should study the influence of temperature variance on the prediction of part quality. Present research only includes the major forming step. Future research should model all forming steps. Furthermore, springback phenomena can be modelled to investigate its effect on part quality. The present work has applied methods and approaches to a single car part, the Volvo XC90 front door inner. Future research should also investigate whether the observed trends and results are valid for other parts as well.

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