IOP Conf. Series: Materials Science and Engineering **159** (2016) 012021 doi:10.1088/1757-899X/159/1/012021

Friction and lubrication modeling in sheet metal forming simulations of a Volvo XC90 inner door

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Abstract. 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. Although friction is of key importance, it is currently not considered in detail in stamping simulations. This paper presents a selection of results considering friction and lubrication modeling in sheet metal forming simulations of the Volvo XC90 right rear door inner. For this purpose, the TriboForm software is used in combination with the AutoForm software. Validation of the simulation results is performed using door inner parts taken from the press line in a full-scale production run. The results demonstrate the improved prediction accuracy of stamping simulations by accounting for accurate friction and lubrication conditions, and the strong influence of friction conditions on both the part quality and the overall production stability.

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 an earlier work of the authors for a U-bend application [1].

At the Stamping CAE & Die Development Department at Volvo Cars, it is concluded that friction and lubrication modeling is the way forward for improving stamping simulation accuracy. This paper presents a selection of results considering friction and lubrication modeling in stamping simulations of the Volvo XC90 right rear door inner, demonstrating the strong influence of tribology and friction conditions on both the quality of the door inner part and the overall production stability.

First the overall project approach will be outlined. Next, the production process of the door inner part and the corresponding stamping simulation models will be introduced. A description of the project results including validation of the simulation results based on door inner parts taken from the press line is provided next. Finally, the conclusions and points of future work are described.

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2. Approach

The approach followed in this work is visualized in Figure 1 whereby the TriboForm software is used in combination with the AutoForm software.

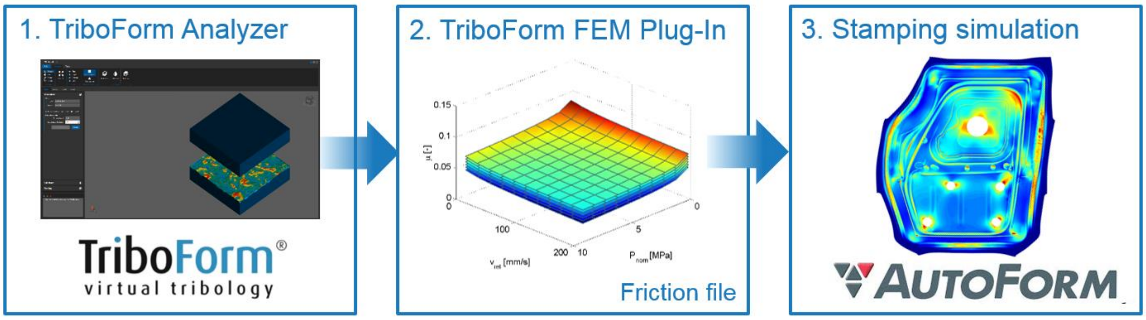

Figure 1. Approach for friction and lubrication modeling in sheet metal forming simulations

The modelling approach comprises three steps. In step 1, a TriboForm friction analysis is performed on a user-defined metal-lubricant combination (see Section 2.1). A friction model is generated for the selected metal-lubrication combination, which can be exported to a friction file (see Section 2.2). Finally in step 3, the generated friction file can be used in AutoForm by making use of a TriboForm FEM Plug-In as described in Section 2.3.

2.1. Simulation of friction and lubrication conditions

Tribological conditions in metal forming processes are dependent on local process and lubrication conditions, loading and local strain state of the sheet material as demonstrated in [2, 3]. Before starting a TriboForm friction analysis, information of the tribology system is required as a user input, i.e. the applied sheet material, coating and tooling material, lubrication type, lubrication amount and process conditions. This information can either be entered by the user or extracted from a database, i.e. the TriboForm Library, as further described in Chapter 3.

The TriboForm software allows for multi-scale modeling of a time and locally varying friction coefficient under a wide range of process conditions. The physically-based models included in TriboForm enable friction modeling in the mixed lubrication regime. This is achieved by coupling a boundary lubrication friction model [4] and a hydrodynamic friction model [5].

The boundary lubrication model includes models to describe the change in tribological properties during forming due to normal loading, deformation of the underlying bulk material and sliding. The models provide an expression for the fractional real contact area, used as an input for the friction calculation. Shear stresses at the interface are obtained by accounting for the influence of ploughing and adhesion during sliding. For this purpose, the plateaus of the deformed sheet asperities are assumed to be perfectly flat, in which tool contact patches (a collection of neighboring tool asperities that are in contact) are penetrating. The shear stress acting on individual contact patches is calculated based on the theory described by Challen and Oxley [6]. By adding the individual contributions of all contacting tool patches, the boundary shear stress τ_{asp} can be obtained.

The calculated deformation of sheet asperities is used to calculate the volume of the lubricant entrapped into non-contacting surface pockets. This information is subsequently used to calculate the fluid film thickness h and the hydrodynamic pressure distribution p_{lub} (i.e. the load carrying capacity of the lubricant). To solve p_{lub}, an FE approach has been adopted as described in [5], introducing hydrodynamic contact elements with additional pressure degrees of freedom. The viscous shear stress at the fluid–solid interface τ_{lub} is calculated based on the obtained hydrodynamic pressure distribution. The summation of the shear stress acting between contacting surface asperities τ_{asp} and the shear stress acting at the fluid-solid interface τ_{lub} is used to obtain the desired coefficient of friction μ, see Equation 1.

$$\mu = \frac{\tau_{asp}+\tau_{lub}}{p_{nom}} \tag{1}$$

2.2. Friction model
The TriboForm software calculate friction coefficients for a predefined range of process settings, i.e. local contact pressures, relative sliding velocities, plastic strains in the sheet material and interface temperatures. A four dimensional matrix is constructed containing friction coefficients for all possible combinations of process settings. To use this data-set within large scale FE simulations, and to guarantee computational efficiency, a four dimensional model is adopted to describe the calculated data points which is stored in a friction file (see Figure 1). Using the TriboForm software, a friction file can be created per tribology system, i.e. the sheet and tooling materials, coatings and lubricants used in actual metal forming production. A friction file has to be constructed only once for a specific tribology system, after which it can be used in different FE forming simulations where the same combination is used.

2.3. Stamping simulations
Next, the friction file is easily imported into the commercial FE software AutoForm using the TriboForm FEM Plug-In. That is, if an AutoForm simulation is started, the FEM Plug-In reads the friction file from TriboForm and enables the usage of the friction model within the AutoForm simulation. As a result, the constant coefficient of friction in AutoForm is replaced by a friction model. Instead, a local- and time-dependent (nodal) friction coefficient is computed each increment and used in the computation of the equilibrium of the finite element model for the materials, coatings and lubricants used in actual metal forming production of the door inner part.

3. Door inner production
An impression of the door inner part highlighted in the all-new Volvo XC90 is shown in Figure 2. The quality of the door inner part is strongly dependent on the friction and lubrication conditions in the actual production process. For varying production conditions, like stroke rate, cushioning force or lubrication conditions, the door inner part can either show wrinkling or fracture as indicated in the right images in Figure 2. Moreover, in the course of a production run, these quality issues can either appear or disappear based on the drift of the actual process conditions like tooling temperature during the production run.

It is known in production that by changing the process- or lubrication conditions, these quality issues can be prevented. The aim of this work is to account for realistic friction and lubrication conditions in stamping simulations to improve the simulation accuracy and enable the detection and prevention of tribology related quality issues in the virtual design process.

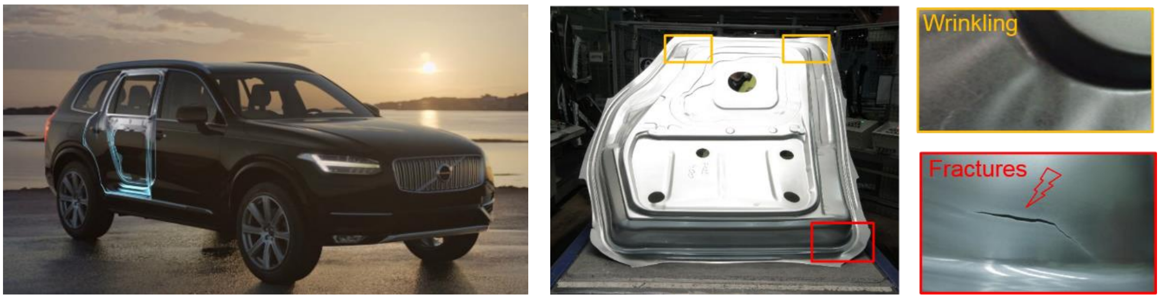

Figure 2. Right rear door inner highlighted in the Volvo XC90 (left) and potential areas of quality issues like wrinkling and splits in production (right).

3.1. Tribology system: sheet – lubricant – tooling
The door inner part is produced using a VDA239 CR4 GI sheet material with a thickness of 0.7 mm and an EDT surface finish. The material tests and data for the BBC2005 material model is determined according to the methodology as described in [6]. The data used in the study are presented in Table 1 and Figure 3.

Table 1. 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
156.6	160.0	156.0	187.0	1.81	1.34	1.88	0.98	4.5

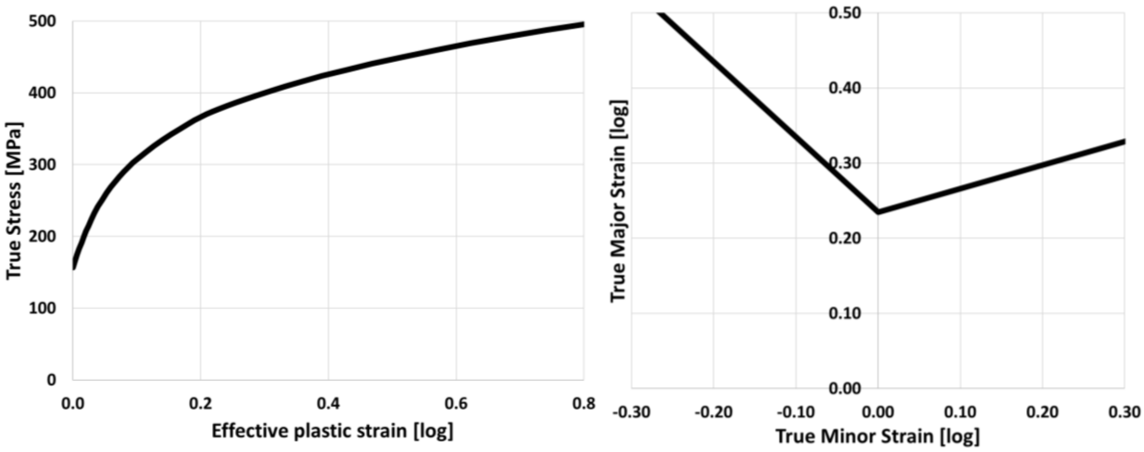

Figure 3. Hardening curve (left) and Forming Limit Curve at onset of localization (right) used in the forming simulations.

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 at different locations on both sides of the sheet. An average value of 2.0 g/m^2 will be used in the following numerical studies. Future work will include numerical studies on the influence of (variation of) lubrication amount, distribution and type. A temperature dependent relation for the viscosity of the lubricant is provided by Fuchs Schmierstoffe GmbH and implemented in the TriboForm software.

The tooling material type is nodular iron GGG70L. The tools are hardened at the positive tool radii and chrome plated at selected areas. The actual tooling geometries have been determined by 3D scanning and implemented in the forming simulations. The scanned data of the blank holder and addendum of the die has been morphed with the deformed surfaces from a structural FE-analysis as a guide. This FE-analysis studies the complete die and press structure loaded with the blank holder force used in production.

3.2. Full-scale production run

A full-scale production run of 1700 parts is performed at a mechanical transfer press-line at Volvo Cars in Olofström, Sweden. The corresponding velocity profile is recorded and implemented in the forming simulations. The blank is contour cut from a 1700 mm wide coil and the pitch is 1553 mm. The stroke rate is set (and limited) to 8 strokes/min. Increasing the stroke rate for the current tribology system results in wrinkles in the part as shown in Figure 2.

3.3. Friction simulations

The friction and lubrication conditions corresponding to the materials and lubricants used in actual door inner production are simulated using the TriboForm software R1.0. As an input for the friction calculations, the real 3D surface topographies of the sheet and die surfaces are required. This information can be imported by the user or extracted from the TriboForm Library.

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In this work, the virgin CR4 GI sheet surface topographies have been measured by 3D confocal microscopy, see Figure 4 (left) for an impression. These measurements have been performed for the sheet material by Tata Steel and imported in the TriboForm software. The die surfaces have been measured by the Volvo Cars at varying locations using epoxy replicas. A single representative chrome plated die surface measurement is taken and used in the TriboForm software for the friction calculations, see Figure 4 (right). Figure 5 (left) shows the projection of the measured die surface topography and the sheet surface topography with a predefined amount of lubricant in the TriboForm software.

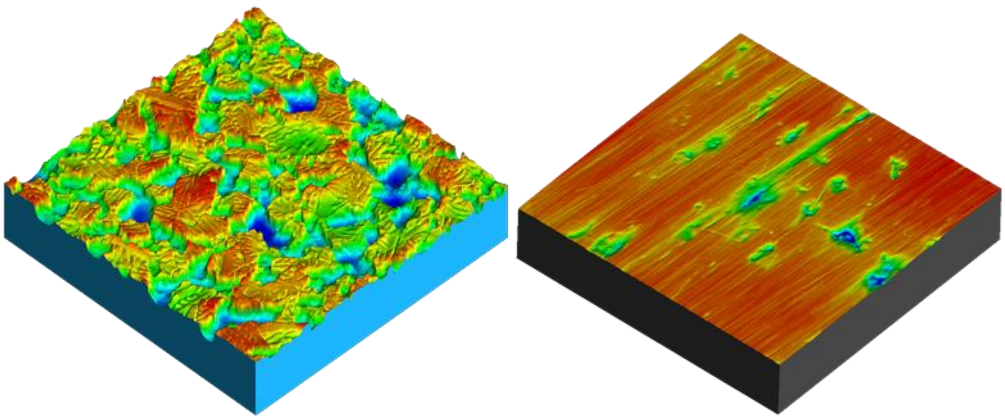

Figure 4. Impression 3D surface texture sheet (left) and tooling (right).

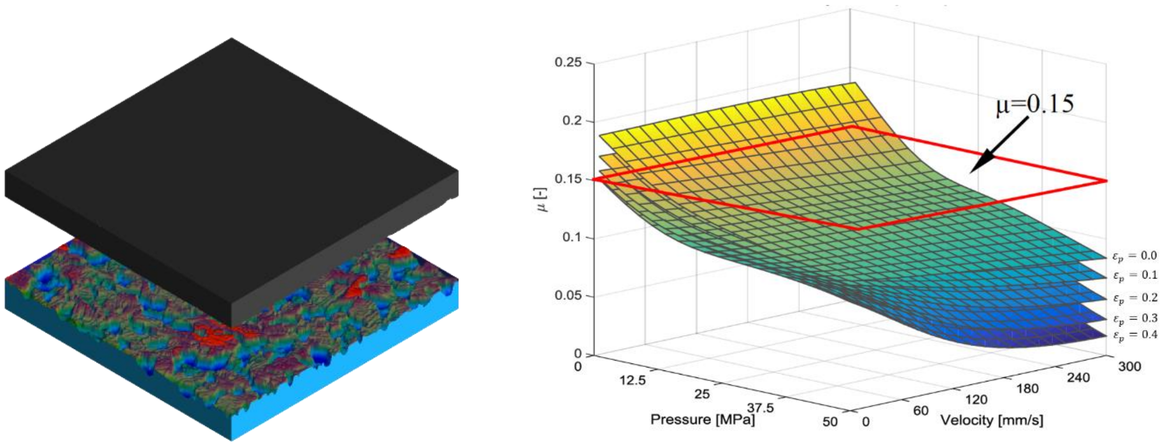

Figure 5. Projection of the die surface- and lubricated sheet surface topography in the TriboForm software (left) and the simulated friction behavior for different strain levels in the sheet material (right)

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

3.4. Sheet metal forming simulations
The door inner forming process is simulated with AutoForm^{plus} R6.0. The scanned and morphed tooling surfaces have been implemented, thus also including geometrical draw-beads. The BBC2005 material model is used for all simulations. The ram speed in the simulation is taken identical to the ram speed of the mechanical press-line.

4. Results
Following the approach presented in Figure 1, the first step is to execute the friction calculations. The resulting friction behavior will be described in Section 4.1. The friction results are then exported from the TriboForm software and imported in AutoForm. Section 4.2 will described the forming simulation- and experimental validation results.

4.1. Friction and lubrication modeling in sheet metal forming simulations
The projection of the measured die surface topography onto the measured sheet surface topography as shown in Figure 5 (left) is the basis for the simulation model used for the friction calculations in TriboForm. The friction conditions are calculated by loading and sliding the die surface over the sheet surface for a lubrication amount of 2.0 g/m^2 and pre-defined ranges of process conditions, i.e. contact pressure, relative sliding velocity, plastic strain in the sheet material and interface temperature. The calculation times of the friction analyzes range between 5 and 10 minutes on a standard quad-core desktop computer.

Figure 5 (right) displays the simulated friction behavior. It shows that the friction behavior is dependent on both contact pressure, relative sliding velocity and plastic strain in the sheet material. Each friction surface is valid for a certain plastic strain in the sheet material. As the plastic strain increases from 0 to 0.4, with an interval of 0.1, the friction coefficient decreases.

4.2. Forming simulations and experimental validation
Forming simulations are performed whereby only the description of the friction conditions is changed. Simulations are performed using the friction model as presented in Section 4.1 and the Coulomb friction model. Regarding the latter, sheet metal forming simulations are generally performed at Volvo Cars using a value for the coefficient of friction of 0.15 for steel sheet which is therefore taken as a reference in this work.

The forming simulation results are validated using strain, draw-in and geometry measurements on door inner parts picked out from the press line at different times in a full-scale production run. This work will present the validation results for a part picked at the start of the production run. The difference in true major strain from forming simulations and measurements on the upper surface are presented in Figure 6. In red areas, the simulation overestimates the major strain, while in blue areas is the simulation underestimates the strain. Using a constant friction coefficient of $\mu = 0.15$ results in too large major strains in several areas, especially in vertical walls. Using the TriboForm friction file will results in lower friction coefficients in areas with high contact pressures, e.g. in radii and draw beads, and also in areas with high relative velocity between the sheet and the die surfaces. This results in a better agreement between simulated and measured major strains. The comparison for the minor strains show the same trend, i.e. that the accuracy of the sheet metal forming simulation results increase using the TriboForm friction file.

The validation of the draw-in results are presented in Figure 7 represented as the 3D position of the edge of the part projected on a horizontal plane. The simulated draw-in results are strongly dependent on both an accurate description of friction and geometrical description of the actual tools and draw-beads. A deviation between production draw-in results and simulation results using a coefficient of friction of $\mu = 0.15$ is observed. The simulation results using the TriboForm friction file still show a deviation in some areas with the experimental draw-in results, but generally show an improved simulation accuracy.

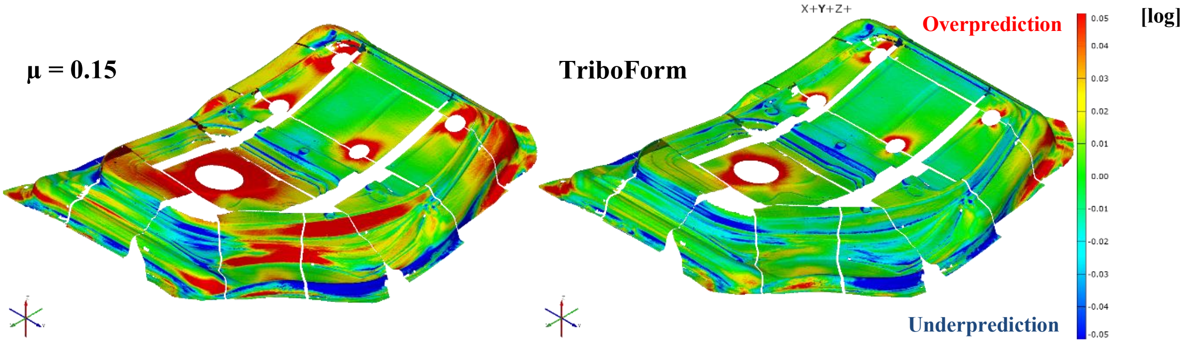

Figure 6. Difference in true major strain between simulations and experimental measurements.

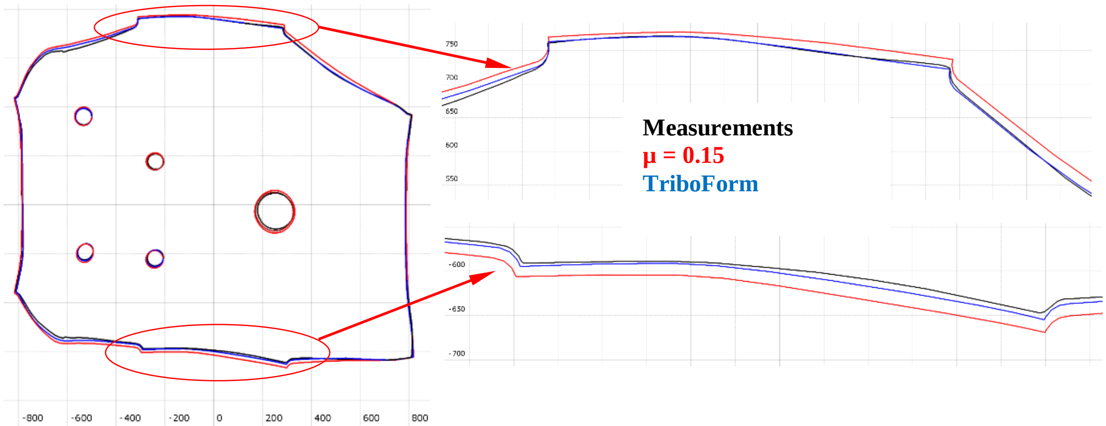

Figure 7. Experimentally measured and simulated draw-in results for the door inner part

The part shape after forming is displayed in Figure 8. With a constant friction coefficient of μ = 0.15 there are no wrinkles on the part predicted. However, with the TriboForm friction file there are two wrinkles on the addendum predicted. The parts that were picked out at the production line had these wrinkles as well. Once again this demonstrates that forming simulations using the TriboForm friction file show a better agreement with measurements and observations made in production.

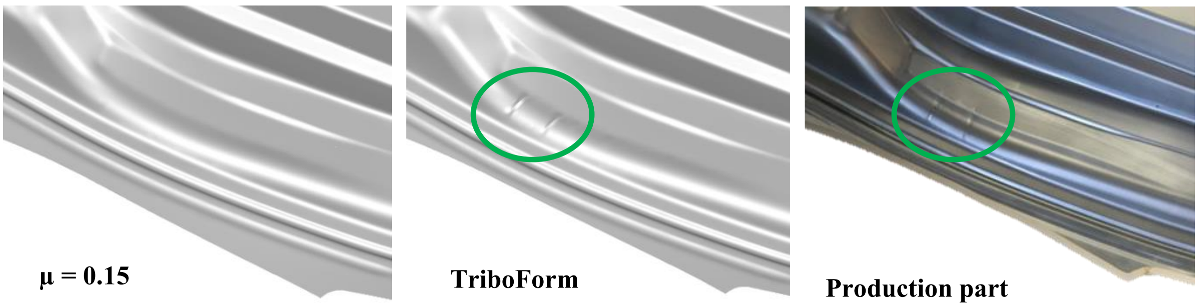

Figure 8. Simulated and actual part shape after forming showing wrinkles on the addendum

5. Conclusions and future work

The results presented in this paper demonstrate the strong influence of tribology and friction conditions on both the quality of the door inner part and on the overall production stability. Moreover, it demonstrates that accounting for realistic and accurate friction and lubrication conditions bring metal forming simulations to a higher level and improve the prediction accuracy of stamping simulations.

Major benefits of the presented approach for Volvo Cars are the following. First of all, the TriboForm software is based on physical models with input parameters that can be efficiently collected from a database or measured with minimal effort. This enables to accurately predict the results of sheet metal forming operations before manufacturing the dies. Secondly, it enables the simulation of friction for the materials and lubricants used in actual production of automotive parts and reduces the demand for experimental testing and try out. Overall, it enables Volvo Cars to further reduce lead time and development cost through the use of more accurate stamping simulations with enriched simulation functionalities.

Future work will include more detailed simulation studies on the effect of varying tool coatings and sheet coatings on the quality of the door inner part. Moreover, future work will focus on numerically studying the influence of temperature dependent friction and lubrication conditions and the resulting transient effects in sheet metal forming production and its effect on the overall production stability. Also the strain rate effects of sheet material will be included in future studies.

Acknowledgement
The authors are grateful for the financial support from Volvo Cars.

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