FINAL DRAFT
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This file will be replaced in Diva before final publication.
Dedicated to
Josefin, Algot, Vincent, Mio, and Lisen.
I love you!
Acknowledgements

This thesis presents research that has been carried out at the Department of Mechanical Engineering at Blekinge Institute of Technology and the department Stamping CAE & Die Development within Manufacturing Engineering at Volvo Cars.

I would first like to extend a special thanks to my supervisors, Professor Sharon Kao-Walter at the Blekinge Institute of Technology and Doctor Mats Sigvant at Volvo Cars. Your guidance and our countless valuable discussions have continuously challenged me in a positive way. I believe that we all derive motivation, along with new and interesting experiences, from learning and working together.

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Finally, the endless love, joy, and patience that I have received from my family are worth everything to me. Thank you! You are the loves of my life!

Hällevik, November 2017

Johan Pilhammar
Abstract

Never before has the car industry been as challenging, interesting, and demanding as it is today. New and advanced techniques are being continuously introduced, which has led to increasing competition in an almost ever-expanding car market. As the pace and complexity heightens in the car market, manufacturing processes must advance at an equal speed.

An important manufacturing process within the automotive industry, and the focus of this thesis, is sheet metal forming (SMF). Sheet metal forming is used to create door panels, structural beams, and trunk lids, among other parts, by forming sheets of metal in press lines with stamping dies. The SMF process has been simulated for the past couple of decades with finite element (FE) simulations, whereby one can predict factors such as shape, strains, thickness, springback, risk of failure, and wrinkles. A factor that most SMF simulations do not currently include is the die and press elasticity. This factor is handled manually during the die tryout phase, which is often long and expensive.

The importance of accurately representing press and die elasticity in SMF simulations is the focus of this research project. The research objective is to achieve virtual tryout and improved production support through SMF simulations that consider elastic die and press deformations. Loading a die with production forces and including the deformations in SMF simulations achieves a reliable result. It is impossible to achieve accurate simulation results without including the die deformations.

This thesis also describes numerical methods for optimizing and compensating tool surfaces against press and die deformations. In order for these compensations to be valid, it is imperative to accurately represent dies and presses. A method of measuring and inverse modeling the elasticity of a press table has been developed and is based on digital image correlation (DIC) measurements and structural optimization with FE software.

Optimization, structural analysis, and SMF simulations together with experimental measurements have immense potential to improve simulation results and significantly reduce the lead time of stamping dies. Last but not least, improved production support and die design are other areas that can benefit from these tools.

Keywords: Sheet Metal Forming, Stamping Die, Stamping Press, Structural Analysis, Finite Element Simulation, Optimization, Digital Image Correlation, Inverse Modeling
Sammanfattning

Aldrig tidigare har bilindustrin varit så utmanande, intressant och spännande som idag. Ny och avancerad teknik introduceras i en allt snabbare takt vilket leder till ständigt ökande konkurrens på en, nästan ständig, ökande bilmarknad. Den ständig ökande komplexiteten ställer även krav på tillverkningsprocesserna.

En viktig process, som denna licentiatuppsats fokuserar på, är pressning av plåt. Tillverkningstekniken används för att forma plåtar till dörrpaneler, strukturbalkar, motorhuvvar, etc. Plåtar formas med hjälp av pressverktyg monterade i plåtformningspressar. Plåtformningsprocessen simuleras sedan ett par decennium tillbaka med Finita Element (FE) simuleringar. Man kan på så sätt prediktera form, töljningar, tjocklek, återfjädning, rynkor, risk för försträckning och sprickor m.m. En faktor som för tillfället inte inkluderas i näst intill alla plåtformningssimuleringar är elastiska press- och verktygsdeformationer. Detta hanteras istället manuellt under, den oftast långa och dyra, inprovningsfasen.


Optimering, strukturanalyser och plåtformningsanalys tillsammans med experimentella mätningar har en stor potential att förbättra plåtformningssimuleringar samt reducera ledtiden för pressverktyg. Sist men inte minst, andra positiva effekter är en enklare och smidigare konstruktionsprocess och förbättrad produktionssupport.
List of Appended Papers

The following papers are appended with the overview of the presented research in this thesis. The content and format of the papers remain unchanged.

Paper A


Paper B


Paper C


Paper D

Related Work


Acronyms and Symbols

2D  Two dimensional
3D  Three dimensional
ABAQUS  ABAQUS version 6.14-1
ARC  Area of relevance and contribution
AutoForm  AutoForm plus R6.0
CAD  Computer-aided design
DIC  Digital image correlation
DRM  Design research methodology
FE  Finite element
FLD  Forming limit diagram
H  Hypothesis
Hyperworks  Hyperworks 13.0
ISI  International scientific indexing
MATLAB  MATLAB R2011b
Optistruct  Optistruct 13.0
RQ  Research question
SDD  Simulation-driven design
STL  Stereolithography
TRL  Technology readiness level
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1 Introduction

1.1 Industrial Background

Never before has the car industry been as challenging, interesting, and demanding as it is today. New and advanced techniques are being introduced with increased speed to achieve sustainable development, improved performance, and heightened customer satisfaction. This has led to increasing competition in an almost ever-expanding car market.

As the pace and complexity increase in the car market, manufacturing processes must advance in sync with these developments. An important process, and the focus of this thesis, is the sheet metal forming (SMF) process. Sheet metal forming is used to create door panels, structural beams, and hoods, for example, which are assembled into complete car bodies in subsequent steps of the process. Sheets of metal are formed using stamping dies that are mounted in stamping presses. Figure 1 depicts a schematic view of a press with a stamping die forming a sheet of metal. The SMF process has been simulated for the past couple of decades with finite element (FE) simulations, whereby one can predict strains, sheet thickness, shape, springback, risk of failure, wrinkles, and other factors.

![Rigid die and press structure during SMF](image)

*Figure 1: Rigid die and press structure during SMF [1]*

The development and manufacturing of stamping dies is one of the most costly and time-consuming parts of each car project. A simplified description of the process is that it traditionally consists of a virtual phase followed by a physical phase. The virtual phase entails computer-aided design (CAD), FE simulations, and some structural compensation for negative process conditions. Once the virtual phase is complete, the die is casted, milled, and manually adjusted for a robust production process in its production press. A drawback is that all the changes that are made on the physical die are based on experiments and are not fully implemented in the virtual model, which limits possibilities for production support through numerical simulations and other virtual tools. Scanning and modeling of the physical stamping dies are needed each time for reliable simulation.
support since the FE model of the die does not match the physical die in running production. Figure 2 from Paper C describes this traditional approach.

**Figure 2: Traditional approach for design and manufacturing of dies (Paper C)**

The rework is part of a tryout process in the tool shop that is often followed by subsequent rework steps in the production press. Rework of the forming surfaces consists of removing material from the forming surfaces through milling or abrasive methods or adding material by welding. The rework process is highly manual and time consuming. It can require up to five weeks for a single die, and hundreds of dies are manufactured in each car project. Much of the tryout is devoted to similar problems that are predicted in SMF simulations. These problems appear and reappear during the tryout because press and die deformations as well as dynamic effects arise and influence the forming results. This is due to the use of rigid two-dimensional (2D) die surfaces in the FE models without three-dimensional (3D) representations of dies and press lines. Using only 2D surfaces in the simulations is the traditional approach to save computational power and time. Reliable 3D models of dies are not available during most engineering phases of a car project, and virtual models or approximations of press lines are incredibly rare. Consequently, the majority of industrial SMF simulations assume that the press line and die are rigid structures. Only the metal sheet is deformed in the simulations; the other parts move solely as rigid bodies. However, the obvious reality is that both dies and presses deform and thereby influencing the process. A comparison of Figures 1 and 3 (taken from [1]) in a double-action process visualizes this assumption. Additionally, [2] presents a similar figure for a single-action process and defines a distinction between macro and micro deformations. Macro deformations are global deformations of the press frame, press parts and stamping die while micro deformations are local deformations in the die structure and forming surfaces. Deformations of dies and presses are responsible for much of the disparity between reality and simulations as well as problems that arise when dies are mounted in different presses with separate elastic characteristics in production or during the tryout.
The aim of this research is to reduce lead time and cost by shortening the tryout phase through the development of numerical simulations and measurement techniques that can accurately represent and record the structural behavior of press lines and stamping dies in an efficient way. When virtual models implement the structural behavior, it is possible to develop and apply methods to perform a virtual tryout, which could result in compensated CAD models of the die. The developed methods can also support production and the formulation of new construction methods and guidelines. Figure 4, from Paper C, suggests a new framework compared to the framework in Figure 2. In an ideal scenario, the design would be finalized within a virtual environment. The virtual models are also used in running production to compensate for changing process conditions by optimizing shim thicknesses or other variables in the die structure. The proposed framework for die development and the methods for virtual tryout and production support should also be applicable to other manufacturing processes that include deformations that can be measured and simulated. One such process could be hemming [3], which exhibits many similarities to SMF.
1.2 Research Questions

In order to set up and run SMF simulation models in a reliable and nimble way that is inclusive of the elasticity of dies and press lines, the following research questions must be addressed.

1.2.1 RQ 1
How can FE simulations reliably represent the deflection of presses and stamping dies?

1.2.2 RQ 2
How can virtual rework be used to shorten and support the tryout phase of a stamping die?

1.2.3 RQ 3
How can structural FE analyses of stamping dies and press lines improve production support from SMF simulations?

1.2.4 RQ 4
How can the simulation time be maintained at a reasonable level for industrial dies when the SMF simulation includes elastic die and press deformation?
1.3 Hypotheses

Based on experience, assumptions, and literature, a hypothesis is suggested for each research question. The aim of the research before the licentiate of engineering degree is to prove the feasibility of each hypothesis. The investigation of these hypotheses can also yield new input, knowledge, and research questions for continued work toward the doctoral dissertation.

1.3.1 H1

The deflection of presses can be recorded with DIC systems and then be inverse modeled in FE software with methods such as super elements, modal reduction, optimization techniques, or spring systems.

1.3.2 H2

Virtual rework of die surfaces is proven on small experimental dies. It can therefore be performed on industrial dies as well. It will be crucial to use efficient modeling techniques and to include process parameters such as press and die elasticity. However, the elastic behavior of presses and dies must first be reliably modeled.

1.3.3 H3

Industrial dies in production can be analyzed similarly to dies in the development phase. However, the analysis must include the shape of the forming surfaces, which is often different compared to the simulations before die tryout. Scanning the forming surfaces and including the geometry in the FE models can achieve this.

1.3.4 H4

The literature has suggested several methods, the most promising of which are modal reduction techniques. It will be possible to use these on industrial dies in FE software where 3D elements are available. In simulations using only 2D surfaces, the deformations can be approximated by deforming a die in a 3D model and then transferring the deformed surface shapes to the 2D model.
1.4 Reader’s Guide

This thesis consists of 12 chapters that together describe the background, execution, results, and future challenges of this research.

Chapter 1 Introduction describes the industrial and scientific background of the thesis. It also defines research questions and hypotheses and includes this reader’s guide.

Chapter 2 Research Methodology presents the simulation driven design (SDD) and design research methodology (DRM) that the research employs. It also describes this type of research together with areas of relevance and contributions of the research.

Chapter 3 Related Work and Research Impact contains a literature review in addition to a reference model. It lists the supported areas as well as areas that will be improved.

Chapters 4 through 7 respectively describe the scientific areas of SMF, DIC, structural analysis, and optimization. They also specify and demonstrate how the research applies the different fields.

Chapter 8 Summary of Appended Papers offers a recapitulation of the appended scientific papers and an estimation of their scientific maturity level. The chapter also explains the author’s contributions.

Chapter 9 Results lists the scientific and relevant results for each of the appended papers.

Chapter 10 Conclusion contains a conclusion and short discussion related to each pair of research questions and hypotheses from Chapter 1 in the context of the conducted research.

Chapter 11 Discussion and Future Work consists of descriptions of the missing pieces and future challenges in accomplishing the aim of this research, which is to achieve virtual tryout and improved production support through SMF simulations that consider elastic die and press deformations.

Chapter 12 References provides documentation of the scientific publications that serve as references in this thesis.
2 Research Methodology

The following chapter describes the research methodology for this project. Simulation-driven design contains the specific tools for conducting the research, while DRM guides the project and facilitates visualization of planning and results.

2.1 Simulation Driven Design

The design and manufacturing of stamping dies is presently a combination of virtual CAD models and simulation work as well as manual work at foundries, die shops, and production plants. The virtual tools enable a shorter lead time, more robust processes, and reductions in time and money demands. This thesis investigates areas in which numerical simulation capabilities can be further utilized or expanded in the future. Simulation driven design can describe the concept of driving design and development processes with simulations instead of with experience or manual trial and error. Sellgren [4] has defined SDD as “a design process where decisions related to the behavior and the performance of the design in all major phases of the process are significantly supported by computer-based product modeling and simulation.” This process can yield innovative solutions, explore hypothetical scenarios, offer guidance toward optimum design, and support decision-making early in the development phase [5].

2.2 Design Research Methodology

Design research is a research area that supports and investigates design methods as well as means for improving the design process itself. It is a relatively new area compared to many other engineering areas, such as mechanics, materials, and thermodynamics [6].

Design research methodology can define, describe, and guide both the author and the readers through this research project. The methodology contains many valuable tools and consists of six phases. These phases are linked together and are not linear in time or succession; rather, they should be viewed as a framework through which the research can progress in an iterative process. The phases are as follows [6]:

- Identifying overall topics of interest.
- Clarifying current understanding and expectations.
- Clarifying criteria, main questions, and hypotheses.
- Selecting type of research.
- Determining areas of relevance and contribution.
- Formulating research plan.

These phases are described in this chapter and throughout the thesis.
2.3 Areas of Relevance and Contribution

An area of relevance and contribution (ARC) diagram visualizes the fields that the research project uses and works within. An ARC diagram is normally divided into three categories: contribution, essential, and useful. The diagram in Figure 5 has “Stamping Die Design & Analysis” at its center. The research presented in this thesis supports and engages with this area as its main focus. The two areas of “Numerical Tools” and “Process Knowledge” are used to improve and advance the main area. Numerical tools for structural optimization, SMF simulations, and structural analysis are key for understanding, predicting, and adjusting the behavior and design of stamping dies and production systems. The numerical work also requires verification by and interaction with real-world data. This can be achieved by increasing process knowledge about the elastic and dynamic behavior of dies and presses. Measurements and other means gather the process knowledge, which the numerical environment must reliably represent.

The yellow areas in the diagram indicate essential areas. This research does not study these in detail, but it does use them as valuable input for the simulations. The results of the research can also directly influence CAD tools, die design, and die material.

The blue areas are considered useful. This research regards them as areas that signify preconditions or boundary conditions. They might require analysis and simulation, e.g. lubrication system as input for simulations, but the aim is not to directly modify them based on research results.

2.4 Type of Research

In DRM, research can be either review based or comprehensive. Review-based research is founded on previous research and knowledge, whereas comprehensive research contains results produced by the researcher [6]. All research should begin with research clarification. For this research, this was accomplished by gathering industrial knowledge at Volvo Cars, visiting conferences dedicated to SMF, and
reviewing scientific literature in significant areas. Chapter 1 Industrial Background and Chapter 3 Related Work and Research Impact present this clarification.

Excluding the review-based literature survey, most of the presented research in this licentiate thesis consists of comprehensive descriptive studies [6]. Thereby, a researcher or research team studied several areas, such as structural analysis and optimization of stamping die structures, compensation methods for die surfaces, and methods for measuring and simulating press elasticity and dynamics. The purpose of these studies was to verify hypotheses and build knowledge that can provide a foundation for future work on the research project.

This research also progresses into a prescriptive study that is based on the descriptive and review-based studies. This is the point at which suggestions and solutions for research problems and new discoveries begin to materialize. Future work on the project will be of a more prescriptive character in developing methods to optimize and compensate for stamping die structures. Chapter 11 Future Work defines much of this future focus and aim.

2.5 Research Quality and Validity

Each of the included papers has been peer reviewed and published in international scientific indexing (ISI) journals or conference proceedings. Simulations and measurements have been performed through best practices with Volvo Cars and the Blekinge Institute of Technology’s available tools and equipment. Analysis, data acquisition, and publication of papers have also involved external partners. More information and a summary of each paper are available in Chapter 8 Summary of Appended Papers.
3 Related Work and Research Impact

3.1 Literature Survey

Many research areas related to SMF are relatively mature subjects with regard to both numerical simulations and manufacturing processes. The existing literature is extensive, and there is substantial ongoing research within areas such as FE and material modeling, process development, cold and hot forming, springback, and failure prediction (see e.g. Banabic et al. [7]). However, the research and industry are proceeding at a rapid pace that continuously offers access to new areas and demands. Robustness simulations, friction modeling, and virtual representations of dies and presses belong to these newer areas, wherein more advanced research is in its first decades of progress, and less published research is available.

This research focuses on numerical representations and optimization methods for stamping dies and press lines, with the major aim of reducing the lead time through a virtual tryout process and improving production support from SMF simulations. The most extensive work that is currently available in this area is a doctoral thesis by R.A. Lingbeek [2]. Lingbeek has also identified certain significant areas that are closely related to this thesis, namely springback problems and the manner of translating compensated geometries from FE simulations into CAD geometries. The first paragraph of the summary in Lingbeek’s thesis expresses much of the purpose and questions of this thesis:

Computer-aided engineering (CAE) has significantly expedited product development in the automotive industry. In the process design and planning of deep drawing processes, computer-aided design tools and finite element (FE) simulations are used together in order to achieve a high-quality product within an acceptable time-span. Here, finding the right shape for the forming tools is one of the most important tasks. However, when the tools are manufactured and tested on the prototype press the quality of the prototype parts rarely satisfies the requirements straightaway. Therefore, manual reworking of the forming tools is required. Because reworking is highly time-consuming and because a lot of experience is required by the tool technicians, this is the most significant bottleneck in the process-planning today.

Lingbeek demonstrates convincing and efficient strategies for predicting elastic die and press deformations with numerical methods. A key issue is the sheer size and solver time of the SMF models, which includes representations of tool and press deformations, even for smaller experimental dies. Reduction techniques can evidently result in a drastic decrease in the model size with a minor increase in computational resources. Deformable rigid bodies are the preferred method out of
those presented. Similar methods for die deformations, compensations, and reduction are employed in [8] and [9].

Previous work has identified the accurate and robust representation of the elastic and dynamic press characteristics as a critical factor. Several strategies and methods are applicable to measure press lines and dies. Optical, mechanical, and electrical sensors are among the preferred methods for gathering data for numerical simulations. Publications in this area include [10-13].

The area of structural optimization is also a relatively mature research area. However, the vast majority of stamping dies are still designed according to old guidelines related to casting feasibility, which results in a heavy, boxy type of structure. A reason for not using optimization techniques on a wide scale for die structures could be the challenge of representing the real world with different types of boundary conditions. The cases and loads on a stamping die can be numerous and complex. If measurements and simulations result in a better understanding of these cases and loads, it might enable die structural optimization on a wider scale. Some literature in the area of die optimization is [14-15].

The literature mentioned in this subchapter is foundational for the ongoing research project. A precondition in most of this literature is an existing 3D model of the die structure, either virtual or real, with which to work. This is not the case for much of a real car project. Thus, the work must progress quickly once there is an available geometry, or else one should work with more generic approximations and meta-models early in car projects. Today, most industrial SMF simulations are also conducted with 2D representations of the die surfaces. This can be due to several factors, such as the following:

- Missing 3D information.
- Time and resource constraints.
- Software without possibility for 3D representations.
- Missing characteristics for elasticity and dynamics of press and die.

When working in this field, it is vital to interrogate and challenge the factors from the real process that are included in the FE models as well as the way in which they are included. There is a balance between reaching a satisfying accuracy and the available modeling and solver resources.

Many publications have demonstrated that the goals of this thesis are feasible. Much of the methods from previous literature needs to be adapted to an industrial level in terms of both complexity and input. The mathematical methods for e.g. surface compensation and deformation predictions are likely to be similar to previous work. A more difficult and important part is to model and represent dies, presses, and real-world boundary conditions in a correct, efficient, and robust way. Measurements and numerical techniques are needed to gather information from
the production system in order to enable the representations in FE software. Methods for press characteristics and simulations are demonstrated in [16].

### 3.2 Reference Model

![Figure 6: Initial reference model](image)

Figure 6 establishes an initial reference model. A reference model is a DRM tool for linking references, statements, and assumptions together in a visual and explanatory way [6]. The reference model uses (+) and (–) symbols to indicate whether an increase or decrease in knowledge or amount in one area yields an improvement or deterioration in another related area. The arrows symbolize links that are supported by either references to the research, assumptions (denoted A), or experiences (denoted E). Tatipala et al., for example, have improved the design and robustness of a stamping die through structural optimization, thereby yielding an arrow from “Structural Optimization” to “Quality of stamping dies.” The plus sign at each end of the specific arrow indicates that an improvement in one area corresponds to an improvement in the other area as well.
3.3 Impact Model

Research projects can provide support for one or more areas in the reference model. The supported areas should then produce an improvement through measurable success criteria in other areas. The impact model in Figure 7 visualizes supported and affected areas.

This research supports these areas:

- Understanding of press deformations.
- Structural optimization.
- FE model efficiency and reduction techniques.

Moreover, it aims to improve the following:

- Quality of stamping dies.
- Lead time for stamping dies.
- Quality of SMF simulations.
- Amount and quality of production support.

![Figure 7: Impact model with supported areas (red) and areas that should be improved (green)](image)
4 Sheet Metal Forming Simulations

4.1 Background and Theory of SMF Simulations

All industries that run stamping operations widely use SMF simulations to verify and optimize the manufacturing process for parts produced from sheets of metal. This use has been accompanied by a dramatic reduction in cost and lead time for stamping dies and sheet metal parts. Just a couple of decades ago, SMF simulations were not used at all or were used only on a very limited scale. The main reason for the implementation of SMF simulations is the rapid development of computers. The fundamental scientific theories that these simulations employ are not new, nor is the desire for reduced cost and lead time. The history, use, and challenges of SMF simulations can be studied in [17-19]. The vast majority of SMF simulations today are based on the FE method, which subchapter 6.1 Structural Analysis – Background and Theory describes further.

Before the availability of numerical simulations, stamping dies were designed and manufactured based on experience and trial and error. Theoretical calculations were also performed by hand [20], although such calculations were frequently limited to simple geometries and products. Today, SMF simulations can predict failures such as necking, cracks, and tearing as well as other variables, including form, wrinkles, sheet thickness, and springback.

The simulation software is often reliable in predicting these different results. However, many factors are still missing in the simulations. Table 1 compares the differences between reality and models. As subchapter 3.1 mentions, it is vital to continuously consider which factors are included in the FE model as well as how to include them. Models are, by definition, simpler than reality; however, the simplifications consistently cause simulations to miss certain influences and effects. Additional elements should be included based on new discoveries of theoretical knowledge in fields such as friction, materials, and failure as well as once there is enough computational power to perform the simulations within time limitations and at a reasonable cost. Better models can enable more substantial and advanced simulation support in current and new situations.

The main research focus in the area of SMF has historically been material modeling. Particularly simple models, such as von Mises or Tresca, are inadequate for most SMF simulations and must be extended or replaced. The rapid development and implementation of new materials with novel characteristics has yielded models with various types of hardening, anisotropy, yield loci, E-module degradation, etc. A challenge with the new material models is that they often require an advanced and extensive amount of material testing and characterization. The industry standard during the first decades of SMF simulations has traditionally been Hill´48 for steel and Barlat´89 for aluminum. Hill’48 only requires a yield stress and three R-values (anisotropy) for modeling of the yield surface [7]. Barlat´89 also includes an exponent that governs the shape of the yield surface.
Uniaxial tensile tests are sufficient for a full characterization. The trend is that more advanced material models, such as BBC05 or Yld2000 [7], are more accurate; however, they also require more testing, such as bulge tests. They also require four R-values, four yield stresses, and an exponent for the yield surface shape. Figure 8 depicts the difference of yield surface shapes for Hill’48 and the more advanced BBC’05 for the material VDA 239 CR180BH+GI, a material in production at Volvo Cars.

![Figure 8: Difference in yield surface shapes for VDA 239 CR180BH+GI, using Hill’48 and the more advanced BBC’05](image)

Although the difference in yield surface shape might not appear vast, it can profoundly impact the final simulation results. One example from Volvo Cars is a simulation that was performed with Hill’48 that predicted a severe failure of the material. The design was nonetheless used and manufactured, and it did not result in any cracks in the given position (see Figure 9). A new simulation was performed with BBC’05, which was in the process of being introduced at Volvo Cars, and revealed that the new material model was much more reliable. The prediction of no crack was correct, and the thickness distribution was improved (see Figures 10-11). Additional simulations and comparisons of this kind can be studied in [7].
Figure 9: Relevant area of part with written thickness measurements in millimeters

Figure 10: Relevant area of SMF simulation with VDA 239 CR180BH+GI, using Hill’48; a crack is visible and thickness values (mm) are plotted
Figure 11: Relevant area of SMF simulation with VDA 239 CR180BH+GI, using BBC´05; no crack is present and thickness values (mm) are plotted.

Another crucial factor in SMF simulations is the friction between sheet and forming surfaces. The friction is typically described with one single constant coefficient of friction throughout a simulation; however, this is known to be highly inaccurate [17]. Both numerical and experimental techniques need to be developed in this area. Papers A and B use an advanced friction model that is based on experimental data. Other key factors in SMF simulations are the influence of temperature and failure models. Temperature influences material properties and frictional conditions, among other aspects. The most frequently used failure criterion is the forming limit diagram (FLD) [19]. The FLD has limits, e.g. it is only valid for linear strain paths. The development and implementation of other tools for evaluating damage and failure is imperative in order to obtain more reliable failure predictions. Solutions can include different damage models, nonlinear forming limit diagrams, or both.

The final point is the focus of this thesis: Elastic machines and tools are almost nonexistent in industrial and academic SMF simulations, which reduces or severely limits simulation capabilities for tryout and production support. Effects from elastic deformations during tryout and production are today handled through manual rework instead.
<table>
<thead>
<tr>
<th>FACTOR</th>
<th>REALITY</th>
<th>SIMULATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRODUCTION STROKE RATE</td>
<td>Not constant</td>
<td>Not in the model</td>
</tr>
<tr>
<td>MACHINE</td>
<td>Elastic</td>
<td>Not in the model</td>
</tr>
<tr>
<td>TOOL</td>
<td>Elastic</td>
<td>Rigid</td>
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<td>CHARACTERISTICS OF THE DIRECTION OF DRAW</td>
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</tr>
<tr>
<td>TEMPERATURE</td>
<td>Not constant</td>
<td>Not in the model</td>
</tr>
<tr>
<td>TOPOLOGY OF BLANK HOLDER SURFACE</td>
<td>Not constant</td>
<td>Not in the model</td>
</tr>
<tr>
<td>MATERIAL</td>
<td>Complex</td>
<td>Simple models</td>
</tr>
<tr>
<td>MATERIAL CHARACTERISTICS</td>
<td>Not constant</td>
<td>(Not) constant</td>
</tr>
</tbody>
</table>

Table 1: Comparison in reality and in the simulation model; table reproduced from [17]
4.2 Application of SMF Simulations in this Thesis

This chapter describes the application of SMF simulations in this research. Paper A and Paper B used these through the software AutoForm\textsuperscript{Plus} R6.0. AutoForm is software that is based on an implicit FE code and focuses entirely on SMF.

A study related to friction was conducted on the real die producing rear inner doors for the Volvo XC90. Paper A evaluates and demonstrates the TriboForm friction model in SMF simulations. Paper B also includes parts of the friction study. Measurements of forming surface roughness, sheet surface roughness, and lubrications properties together with simulations were used to create a friction model depending on contact pressure, relative velocity between sheet and die, and plastic strain of the sheet. Both Paper A and Paper B present more details on the friction study and the specific friction model.

![Figure 12: Approach for friction and lubrication modeling in SMF simulations (from Paper A)](image)
Figure 13: Over and under prediction of simulated strain compared to measurements; simulation using compensated die surfaces and a friction coefficient of 0.15 (from Paper B)

Figure 14: Over and under prediction of simulated strain compared to measurements, simulation using compensated die surfaces and TriboForm friction model (from Paper B)
The resulting geometry of the part does not differ significantly depending on the friction coefficients or models that the SMF simulations apply. However, there is an apparent impact on the strain prediction. Figures 13 and 14 depict the difference between a simulation with a friction coefficient of 0.15 and the TriboForm friction model. The results in the figures illustrate the disparities between major strain as measured on a real door panel in production and major strain as predicted with SMF simulations. The TriboForm results can be approximately replicated with a friction coefficient of 0.12. It is true that the friction coefficient can be adjusted to match the geometry and strains for most cases. The purpose of a physically based friction model is to predict friction instead of inverse modeling it.

Nevertheless, friction is not the main topic of this thesis. The primary reason for including Paper A is that it was not possible to conduct the SMF simulations that it presents without including elastic die deformations. The SMF simulations yielded incredibly inaccurate results when using scanned die geometries from the production die. The stamping die and its forming surfaces needed to be deformed with production forces in a structural FE model. Paper A therefore serves as a valuable example of the potential importance of including elastic deformations of stamping dies and presses in many SMF simulations.

Paper B describes and demonstrates a strategy for considering these elastic die and press deformations in SMF simulations. The forming surfaces of the existing stamping die were scanned to produce 2D surfaces. The shape of the 2D surfaces was then modified based on structural analysis of the complete 3D die structure. The structural FE model of the die was loaded to represent the closing of the blankholder. The structural analysis of the die was not included or coupled with the SMF simulations because Autoform currently does not offer this possibility, as it only uses 2D representations of the die surfaces.

Paper B contains the detailed structural study of the die and SMF simulations. Figures 15 and 16 present the major result of the study by depicting the resulting sheet geometry compared to the actual draw in curve scanned from a real part. It is apparent that inclusion of the die deformations was essential for accurate simulation results in this case.
Figure 15: Sheet metal forming simulation without compensated die surfaces compared with scanned draw in curve (from Paper B)

Figure 16: Sheet metal forming simulation with compensated die surfaces compared with scanned draw in curve (from Paper B)
5 Digital Image Correlation

5.1 Digital Image Correlation – Background and Theory

Digital image correlation is an optical measurement technique for analyzing a variety of engineering problems [21] that range from large objects, such as buildings and vehicles, to material samples on a sub-millimeter scale. In this technique, at least one camera captures a series of images that are analyzed in a subsequent post-processing step.

The technique builds on a basic assumption regarding an object that is illuminated by a light source. This object is covered with some kind of pattern or with point references. By examining a series of images that are taken during a measurement, it is possible to compare the light intensity in images to a reference stage and subsequently identify and calculate the displacement of each point in both the reference and the current image [21]. Analysis techniques have evolved over time to become increasingly powerful, and stress, strain, and deformation analyses presently use the technology on a relatively wide scale, often coupling it with measurements of other variables, such as temperature or force. Displacement measurements generally occur on a sub-pixel scale [22].

One of the most powerful advantages of DIC is the possibility of full-field measurements. For example, a classical tensile test normally yields only stress and strain as an average across the test sample. In contrast, DIC can obtain stress and strain values for the entire measurement area (see Figure 17 for an example). This enables a much more detailed and advanced material analysis. Use of 3D cameras can even produce results that lie outside of a plane. Full-field measurements also provide a valuable and reliable opportunity to bridge the gap between experiments and simulations through stress and strain analyses [22].

Figure 17: Example of a DIC measurement of a full-field tensile test with a speckle pattern, showing major strain in top image
Some examples of DIC applications include the following [22]:

- User will be available to check if boundary conditions correspond to those desired.
- Optical control of experiments opposed to gauges and extensiometers.
- Full field, as mentioned before, e.g. for identification of material properties.
- Contactless studies of experiments in hostile environments for humans, gauges, or both.

5.2 Thesis Application of DIC

Paper D applies DIC to study displacements of a loaded stamping press. The paper investigates how to model the elastic behavior of a press table in an FE model. The research used a stereo camera to capture the displacement of point references placed across the various parts of the press. Figure 18 offers an example from the measurements with displacement vectors for each reference point on the press table. The lengths of the vectors correspond to the displacement of each reference point in the z-direction, or height direction, of the press table. The pillars that are visible in the figure are loaded with the outer ram of the press and were placed in different positions during the measurements in order to capture maximum press characteristics. The displacement data were then used together with the forces to inverse model a virtual model of the press table, as described in Chapter 7 Structural Optimization.

![Example of DIC measurement of a full-field tensile test with a speckle pattern, showing major strain in top image](image)

**Figure 18:** Example of a DIC measurement of a full-field tensile test with a speckle pattern, showing major strain in top image
6 Structural Analysis

6.1 Structural Analysis – Background and Theory

The most common and explanatory definition of structural analysis is that it assesses the effect of loads on structures. The structures can be of almost any type, including cars, bridges, concrete buildings, beams, or gravel roads, or even of a biological nature, such as the human body. The loading normally consists of forces, temperatures, and acceleration, while the effects on the structures are results such as stresses, reaction forces, or deformations.

Structural analysis is not a separate and isolated field of science. Rather, it resembles a collection of applied theories from mathematics, material science, and mechanics. These scientific fields are used together to create theories for more or less advanced structures, such as beams, rods, plates, and combinations of these. The theories are often founded on assumptions and experiments and are mathematically described through differential equations. Models always require some form of verification, often by physical testing.

Traditional forms of structural analysis consist of analytical methods that can be calculated by hand on paper. The primary use of structural analysis is to verify the requirements on structures based on their loading. The verification process almost always considers safety factors and design codes that take into account errors in assumptions, material variations, and load variations. The simplest analytical methods consider simple geometries and loads, support conditions, and elastic material properties. Nevertheless, they are extremely useful, as most structures can be simplified into a single, simpler component or set of such components. There are also more advanced methods available that consider dynamic loading and responses, plastic material models, and non-linear behaviors of the analyzed structures. Most of these theories are based on continuum mechanics that consider the relationship of equilibrium, constitutive model, and compatibility [23-24].

Numerical methods have been increasingly applied since the arrival of computers and ever-increasing computational power. These methods are based on the same theories as the mentioned analytical method. The most widespread method today is the FE method, which is an approximate solution method for differential equations [25-26]. By using the FE method to connect a finite number of elements by a finite number of nodes (see Figure 19), nearly any structure can be discretized, constrained, loaded, and solved for any problem, provided enough computational power is available. Both FE and analytical methods are highly accurate as long as valid assumptions and simplifications are used together with a sufficiently accurate discretization of the analyzed system.
The following paragraphs and equations describe the basic steps of configuring an FE formulation for an arbitrary differential equation. The examples are based on the methods and equations described in [26], mainly from Chapter 8.

The most common way to define a differential equation is through the so-called “strong form.” This form has an exact mathematical solution in every point and requires boundary conditions to be solved. Equation 1-3 exemplifies the strong form of one-dimensional (1D) heat flow.

\[
\frac{d}{dx} \left( Ak \frac{dT}{dx} \right) + Q = 0; \quad 0 \leq x \leq L \quad (1)
\]

\[q(x = 0) = - \left( k \frac{dT}{dx} \right)_{x=0} = h \quad (2)\]

\[T(x = L) = g \quad (3)\]

The FE method, however, is based on the “weak form” of differential equations. The weak form is obtained by multiplying the differential equation by a weight function \( v \) and then integrating the expression by parts over the relevant area. The weak form of Equation 1-3 is

\[
\int_0^L \frac{d}{dx} \left( Ak \frac{dT}{dx} \right) dx = -(vAq)_{x=L} + (vA)_{x=0} h + \int_0^L vQ dx \quad (4)
\]
\[ T(x = L) = g \]  

(5)

After obtaining the weak formulation of the problem, an element-wise approximation is made of the unknown function, and the weight function \( v \) is chosen. The argument in [26] is that a suitable weight function should be chosen via the Galerkin method, which is an example of a so-called “weighted residual method.” An example in [26] illustrates the Galerkin method, from which the following description originates:

Equation 6 is a 1D differential equation:

\[ Lu + g = 0; \quad a \leq x \leq b \]  

(6)

where \( u(x) \) is an unknown function, \( g(x) \) is a known function, and \( L \) is a differential operator. Boundary conditions are given by

\[ u(a) = u_a; \quad u(b) = u_b \]  

(7)

which implies that the equation is a second-order differential equation. Equation 6 is multiplied by weight function \( v \) and integrated from \( a \) to \( b \).

\[ \int_{a}^{b} v(Lu + g)dx = 0 \]  

(8)

Since the equation will be solved by a numerical solution, a trial function is needed: \( u^{app} \).

\[ u^{app} = \psi a \]  

(9)

where

\[ \psi = [\psi_1 \quad \psi_2 \quad \ldots \quad \psi_n]; \quad a = \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_n \end{bmatrix} \]  

(10)

In an element-wise approximation, \( a_1 \ldots a_n \) would be the nodal values of \( u \), while \( \psi_1 \ldots \psi_n \) would be the global shape functions [26]. However, the objective is generally to determine the parameters \( a_1 \ldots a_n \), and \( \psi_1 \ldots \psi_n \) can be chosen arbitrarily.

\( u^{app} \) may then be substituted into Equation 8, yielding

\[ \int_{a}^{b} v(Lu^{app} + g)dx = 0 \]  

(11)

and
\[ Lu^{\text{app}} + g = e \]  

(12)

where \( e(x) \), termed the residual, is a measure for the error as \( u^{\text{app}} \) generally will not satisfy the equation exactly. With Equation 12, Equation 11 can be written as

\[
\int_{a}^{b} v e dx = 0. \tag{13}
\]

where \( v \) is an arbitrary weight function, and \( e \) depends on the parameters \( a_1 \cdots a_n \). The objective is thus to choose a weight function to allow for determination of these parameters. The resulting weighted residual methods depend on the selected weight function. Additionally, [26] further demonstrates that \( a \) can be determined by solving the linear system of equation in Equation 14

\[
K a = f \tag{14}
\]

where

\[
K = \begin{bmatrix}
\int_{a}^{b} V_1 L(\psi_1) \, dx & \cdots & \int_{a}^{b} V_1 L(\psi_n) \, dx \\
\vdots & \ddots & \vdots \\
\int_{a}^{b} V_n L(\psi_1) \, dx & \cdots & \int_{a}^{b} V_n L(\psi_n) \, dx
\end{bmatrix} \tag{15}
\]

and

\[
f = - \begin{bmatrix}
\int_{a}^{b} V_1 g \, dx \\
\vdots \\
\int_{a}^{b} V_n g \, dx
\end{bmatrix}. \tag{16}
\]

This procedure applies to all weighted residual methods. [26] describes and demonstrates several weighted residual methods. The recommended method in [26] is the Galerkin method, whereby

\[
V_i = \psi_i \quad i = 1, \ldots, n \tag{17}
\]

which yields
\[
K = \begin{bmatrix} 
\int_a^b \psi_1 L(\psi_1) \, dx & \cdots & \int_a^b \psi_1 L(\psi_n) \, dx \\
\vdots & \ddots & \vdots \\
\int_a^b \psi_n L(\psi_1) \, dx & \cdots & \int_a^b \psi_n L(\psi_n) \, dx 
\end{bmatrix}
\]  
(18)

and

\[
f = - \begin{bmatrix} 
\int_a^b \psi_1 g \, dx \\
\vdots \\
\int_a^b \psi_n g \, dx 
\end{bmatrix}.
\]  
(19)

To summarize, formulating a problem through the FE method basically entails the following four steps, as defined in [26]:

“Basic steps in FE formulation

1. Establish the strong formulation of the problem.
2. Obtain the weak form of the problem.
3. Make an elementwise approximation over the entire body of the unknown function, i.e. the temperature T.
4. Choose the weight function \( v \)’”

Finite element formulations of many types of problems can then be solved through various integration schemes that most frequently consist of implicit or explicit methods which has been described in [3]. Many commercial FE software are available for different applications of which ABAQUS used in this thesis is one of the most general. There are also many FE software that specializes in certain areas. AutoForm is an example of a highly specialized software used only for SMF simulations.

6.2 Application of Structural Analysis in this Thesis

Each of the four papers appended to this thesis uses structural analysis. The software with which these structural analyses were performed were ABAQUS v6.14-3 (ABAQUS) and Optistuct 13.0 (Optistuct). Hyperworks 13.0 (Hyperworks) was used as a pre- and post-processor.

The aim of the structural analysis in Paper B was to deform and analyze an existing stamping die by loading it with the same forces as in the real press line. The deformed shape of the die surfaces was then transferred to AutoForm and used in...
a subsequent SMF simulation. Paper A employed the same deformed shape and AutoForm SMF model.

A FE model was created of the relevant parts of the stamping die and press line, as depicted in Figure 20, in order to simulate the die deformations after the closing of the blankholder. The geometry of the forming surfaces in the FE model was initially the nominal surfaces from the original CAD model. These were known to differ significantly from the final die. The forming surfaces were therefore scanned to obtain their correct shapes in the form of 2D stereolithography (STL) surfaces. These surface shapes were then applied to the mesh of the FE model by morphing in Hyperworks.

![Figure 20: Structural FE model of stamping die used in Paper A and Paper B](image)

After solving the FE model, it was obvious that all parts were deforming – especially the blankholder, since it is the weakest part – and that there was a relatively large initial gap of two sheet thicknesses between the surfaces of the blankholder and the matrix. The deformations were then applied to the scanned 2D surfaces through both sub-modeling in ABAQUS and morphing tools in AutoForm in order to run SMF simulations with a correct geometry of the forming surfaces. The method of sub-modeling was found to be the more reliable of the two approaches (see Paper B for more details on this).

The ABAQUS model also explicitly revealed that the die was losing contact with the press cushion on approximately 50% of the cushion pins, which rendered it particularly difficult to achieve a blankholder pressure in several areas. Moreover, the model demonstrated that ABAQUS can visualize a virtual spotting image. Figure 21 depicts the deformation of the blankholder. Figure 22 illustrates the
pressure on the cushion pins, and Figure 23 displays the virtual and real spotting images.

Figure 21: Deformation of blankholder, magnified 250X (from Paper B)

Figure 22: Contact pressure on cushion pins (from Paper B)
Paper C primarily focuses on optimization of the blankholder contact pressure through surface compensation and shims thicknesses. Use of a successful numerical method for optimization of the contact pressure is advisable to improve and control the spotting image and contact pressure that was measured and simulated in Papers A and B. The model that Paper C optimizes is an ABAQUS structural model, which is a highly simplified stamping die that consists of a matrix, a blankholder, and cushion pins. The modified variables in the structural model are the geometry of the forming surfaces and the forces that act on the blankholder spacers. Figure 24 represents the model and highlights the initial pressure distribution on the blankholder surface.

The research for Paper C applied different techniques to modify the geometry of the die surface and the forces that act on the blankholder spacers in order to achieve a uniform pressure distribution in the structural model (see Figure 25).
To predict and control the types of deformations and contact pressures in Papers A-C, it is important to represent the press elasticity in a reliable way. This stipulation was the focus of Paper D. Paper D employs two FE models for structural analysis, both of which were created in Optistruct. The first is a model of a press table used in a structural optimization run. In this model, the amount and position of the material beneath the top part of the press table (blue in Figure 26) was optimized until the deformations of the press table matched the deformations from the deformation measurement of a double-action press.

Another pure structural analysis model, without optimization, was solved to visualize the die deformations of a die on the optimized press table when loaded with production forces. Figure 27 depicts total deformations.
Figure 27: Magnitude of deformations for a die under production loads placed on the optimized press table
7 Optimization

7.1 Optimization – Background and Theory

In recent history, engineers have systematically applied theory and experiments to practically and scientifically determine the best solution. Researchers have developed specific mathematical optimization algorithms that automatically identify an ideal solution to a specific problem. Due to the rapid development of computers in recent decades, these algorithms have become increasingly powerful and useful in a wide variety of scientific fields ranging from mechanical engineering to biology.

It is necessary to create a model before applying any optimization algorithm [27]. This is normally a numerical model if computers are utilized to solve the optimization problem. A definition of a good or best solution is also important, as it would otherwise be impossible to define an objective for the specific routine. Apart from an objective, the optimization routine also needs variables – whether discrete or continuous – that can be altered throughout the optimization process within some given boundaries. These boundaries are typically referred to as “constraints,” and they define the boundaries of a design space.

There is a wide range of optimization algorithms, with their common denominator being that they guide the approach throughout the design space in pursuit of the optimum solution [27]. The most common optimization algorithms are often gradient based and are applied to determine a minima within the design space. This demands a formulation of the design problem in such a way that the optimum solution will be found at the minimum within the design space. There is a wide variety of methods beyond the gradient-based algorithms, and one interesting type of algorithm that often appears in the literature is the genetic algorithm. Genetic algorithms are based on Darwin’s theory of evolution and “survival of the fittest.” These algorithms are often applied to search for optima in complex design spaces [28].

Another rapidly expanding area within the optimization research field is topology optimization [29-30]. Within engineering, topology optimization is most commonly applied to find the optimum distribution of material in a design volume given specific objectives, variables, and constraints. A typical problem is to reduce the mass of a structure while limiting stress levels below a certain level for a given load.

In real-world engineering, any given problem often has multiple objectives [27]. If the objectives are conflicting, and they often are, there must be a tradeoff between them. Crash safety versus fuel efficiency within the car industry is a prevalent example of competing objectives. Modern optimization routines often present users with a large number of solutions within the design space together with robustness values and tradeoffs for each solution.
7.2 Application of Optimization in this Thesis

Paper C and Paper D apply optimization techniques. The forming surfaces in the structural model of a simplified die (presented in subchapter 6.2) initially yielded an uneven contact pressure distribution. The surfaces were then compensated in order to reach an even pressure distribution. Although the structure was optimized, there was no real optimization algorithm applied during the iterative optimization of the die model. The die surfaces were first loaded with the desired pressure distribution. The resulting displacement of the surface nodes were then exported to MATLAB, which automatically compensated for the nodes so that they were positioned in their original, unloaded position once the die was loaded. Very few iterations were required before the solution converged and the optimum pressure distribution was reached.

![Amount of compensation in the normal direction of the die surface](image1)

**Figure 28:** Amount of compensation in the normal direction of the die surface

![Resulting pressure distribution after surface compensation, compared with Figure 24](image2)

**Figure 29:** Resulting pressure distribution after surface compensation, compared with Figure 24

After completion of the surface compensation, a gradient-based optimization algorithm was applied to a subsequent problem, where it was assumed that wear or changing process conditions were disturbing the contact pressure distribution in
the die. The objective of the optimization was to return to the even pressure distribution that Figure 29 depicts, and it used the forces on the blankholder spacers as the variables. In reality, changing the thickness and amount of shims on these forces can alter them. The constraint is that the forces on the blankholder spacers can only act to separate the die surfaces, not pull the upper and lower part of the die towards each other. The optimization problem is defined as such that the optimization algorithm should minimize an equation that depends on the total force acting on the blankholder surface, the number of nodes in contact, and the difference between the highest and lowest nodal pressure on the blankholder surface. The algorithm commenced from the distribution in Figure 30 and successfully identified the solution depicted in Figure 31.

![Initial pressure distribution for optimization of the forces acting on the blankholder spacers](image1)

**Figure 30: Initial pressure distribution for optimization of the forces acting on the blankholder spacers**

![Resulting pressure distribution after optimization of the forces acting on the blankholder spacers](image2)

**Figure 31: Resulting pressure distribution after optimization of the forces acting on the blankholder spacers**
The optimization in Paper C focuses on the die and the forming surfaces. Paper D also applies optimization, topology optimization in particular, to inverse model the elastic behavior of a press table measured with an ARAMIS DIC system. The forces that act on the real press table were known, as was the resulting deflection of the press table (see subchapter 5.2). A rough numerical model of the press table was then built in Optistruct and subjected to the same loads as the real press table. A topology optimization was then set up to reduce the amount of material underneath the surface of the table. The constraints for the displacement of the nodes on the surface were defined to restrict their movement within the same distance as the nodes on the real press table. This would yield a virtual press table that deforms identically to the real table, since the material underneath would be reduced until it reaches the constrained maximum amount of movement for each node. The final press table that corresponds to the real table is depicted in Figure 32 and can be compared with Figure 26.

Figure 32: Final geometry of the inverse modeled press table in Paper D

Figures 33-35 depict the displacement in the z-direction for the same load cases on the real press table compared to the virtual press table.
Figure 33: Displacement of real press table (left) compared to virtual press table (right) for the same load case.

Figure 34: Displacement of real press table (left) compared to virtual press table (right) for the same load case.

Figure 35: Displacement of real press table (left) compared to virtual press table (right) for the same load case.
8 Summary of Appended Papers

The papers in this thesis work together to answer and support the research questions and hypotheses 1-4 in Chapter 1. The papers have all been peer reviewed and published in ISI conference proceedings or journals. The author has taken primary responsibility for planning and conducting the research as well as authoring and co-authoring all the parts connected to this research project.

The work begins with Paper A, which is predominantly a study and demonstration of the TriboForm friction model in a closely related research project regarding friction. The friction model is based on physical data and depends on contact pressure, plastic strain in the sheet, temperature, and relative velocity between the sheet and die surfaces. Real data was collected from the die, sheet, and a production run with the physical die. Sheet metal forming simulations were then planned with SMF software and the TriboForm friction model using scanned die surfaces. The simulations did not produce reliable results due to the die surface geometries, which did not fit against each other. It was immediately suspected that the die deformation to give the surfaces their shape under loading was missing. The simulations in Paper B resolved this. Regardless, Paper A serves as a valuable and descriptive example of when the inclusion of die and press behavior is key to SMF simulations.

Paper B describes the method of linking scanned die geometries with structural analysis and SMF simulations using 2D surfaces. This link was essential for performing the simulations in Paper A. A coupling of structural analysis and SMF was previously available in software with possibilities for both. The method demonstrated herein suggests how to integrate elastic deformations in SMF simulation software that is currently unable to fully include 3D die and press structures. The deformation of the 3D die structures was performed in one type of software without any metal sheet or forming, the deformations were then transferred to the SMF software, where they were locked in that position throughout the simulation. The drawback is the need to lock deformations in one point in time despite the likely deformation of the die throughout the forming operations. The paper also discusses possible strategies for addressing this continuous deformation in future work, e.g. meta-modeling and contact parameters. The simulations are also particularly valuable in their visualization of deformations and relative motions in the die during the stroke. The scanning of die surfaces in combination with the structural simulation revealed certain unexpected behaviors in the die.

Paper C describes the current situation of die development and manufacturing. Specifically, much engineering work is done with virtual CAD and simulation tools during the development phase. The dies are then manufactured and undergo an intensively manual tryout process before running production. The rework during the tryout is almost always manual and labor intensive, and it thus drives up cost and lead time. Another drawback is that the reworked die geometries are only
partly modeled, if at all, in the SMF simulation models and CAD geometries. This seriously limits the available production support through simulation. Paper C also demonstrates methods of optimizing the die geometries and variables, such as shims in real dies. The optimization, or compensation, of the die surfaces can be a valuable tool for implementing solutions for virtual rework to shorten the tryout phase of stamping dies. Finally, the paper describes a desired future process for die development and manufacturing as well as early suggestions of how to use optimization methods, such as shims, for controlling adjustment mechanisms in the dies. These optimization and control techniques could be beneficial when addressing many of the issues noted in Papers A and B.

Papers A, B, and C all describe different simulation and optimization techniques for stamping dies. Every simulation in future production and experimental cases will also rely on appropriate modeling of press and die elasticity. Paper D therefore studies how to record press deformations with DIC systems, as predicted in FE software, and the influence of press elasticity on die deformations. It is possible to use methods other than DIC to record deformations, but they would need to be recorded in some way to enable their inclusion in and verification of numerical simulation models. The deformations of a double-action press were successfully recorded and post-processed with GOM Inspect and MATLAB. Topology optimization was then employed with the aim of replicating the behavior of the real press table. The method enables the characterization of complete presses without the need to model and include the press itself in simulation models. A stamping die was finally placed on the virtual press table to demonstrate the total amount of deformations to which it was subjected when loaded with simulated production forces. Paper D also initiates a discussion of how to separate or combine macro and micro deformations [2] if the models are used in a virtual try out process.
The following table indicates each paper’s connection to the research questions and hypotheses:

<table>
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<tr>
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<th>Paper A</th>
<th>Paper B</th>
<th>Paper C</th>
<th>Paper D</th>
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<td>H4</td>
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</table>

Table 2: Connections of each paper to research questions and hypotheses
8.1 Paper A

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


Relation to the thesis

Paper A is closely connected to Paper B and serves to highlight the importance of linking structural analysis and SMF simulations. Without the linked simulation models in Paper B, the study in Paper A would have been impossible to conduct. Paper B uses a friction model that demands a robust prediction of contact conditions, which the simulations presented therein do accomplish.

The author's contribution

The author participated in planning and writing the paper and was responsible for simulations that linked the deformations of the die in running production to the SMF simulation model used in the paper. The author also took part in the friction study through experimental data collection and performing simulations.

8.2 Paper B

Title: Introduction of elastic die deformations in sheet metal forming simulations


Relation to the thesis

Paper B demonstrates the criticality of linking SMF simulations, structural analysis, and surface scanning data, especially when analyzing existing dies. Even though the study had limited data about the press elasticity, it reveals that the die deformations can have a substantial impact on simulation results. The paper also describes unexpected behaviors of the stamping die and raises new questions for how to handle deformations in SMF simulations.

The author's contribution

The author was responsible for planning and writing the paper. Moreover, the author created and analyzed simulation models and was the originator of the presented ideas. The results from Paper B enabled the study presented in Paper A. The co-authors mainly contributed through SMF modeling and experience as well as academic guidance during research and writing.
8.3 Paper C

Title: Framework for Simulation-Driven Design of Stamping Dies Considering Elastic Die and Press Deformations


Relation to the thesis

This paper primarily describes methods for surface compensation in stamping dies and investigates how to predict and optimize process variables in dies to facilitate a robust production. This case uses shims as the variables. The paper also details the current die manufacturing process and offers a recommendation for its ideal conduct in the future.

The author's contribution

The author was responsible for planning and writing the paper and took main responsibility for the development and setup of simulation models. The work originated from the author based on studies within the field of structural optimization. The co-authors contributed expertise in the area of optimization and SMF.

8.4 Paper D

Title: Characterizing the Elastic Behaviour of a Press Table through Topology Optimization


Relation to the thesis

Papers A-C strongly indicate a high potential of setting up FE models for virtual rework and analysis of stamping dies. The missing element is the boundary conditions that act on the die structure, which signify the elastic and dynamic behavior of the press lines. Paper D describes a method for loading a press, recording the deformations with a DIC system, and modeling the press table on the basis of the measured deformations.

The author's contribution

The author was responsible for planning and writing the paper as well as for leading the collective work that the paper presents. The author also assumed a dominant role in preparing and performing the DIC measurements and supervised the master thesis students who created the die structural model. Furthermore, the author conducted the post-processing of the DIC measurements, creating the
inverse modeled press table through topology optimization, and running simulations presented in the paper of the stamping die and press table together. The co-authors participated in structural analysis of stamping dies and contributed SMF and DIC expertise.

8.5 Maturity Level of the Papers

Table 2 describes the approximate level of simulation methods and suggested methods in Paper A-D with respect to the technology readiness level (TRL) scale [31]. Basically, TRL 1 represents an idea or initial concept while TRL 9 is a fully industrialized solution in action.

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Table 3: Technology readiness level 1-9 for the appended papers A-D
9 Results

This chapter concisely presents the relevant research results from each of the appended papers. Afterwards, Chapter 10 discusses the results and whether they prove or disprove the hypotheses from Chapter 1.

- Representing the elasticity of full size dies and press lines is crucial when conducting SMF simulations for dies in industrial production. It is feasible and was demonstrated in Paper A and B.

- A strategy was developed for considering die deflections in SMF simulations and software that uses 2D rigid die surfaces. In short, the strategy consists of scanning the forming surfaces and then using the scans during an FE structural analysis without any metal sheet or forming simulation in order to predict die deformations. The resulting geometries of the forming surfaces at blankholder closing are then exported to AutoForm, where they are used as rigid 2D surfaces.

- Structural analysis of dies can visualize their elastic behavior, which is challenging to see or measure. An example of this elastic behavior is relatively large deformations of the blankholder and cushion pins losing contact with the press cushion.

- It is possible to virtually visualize, predict and edit the spotting image of a stamping die.

- A physically based friction is of key importance and yields clear improvements.

- Inclusion of the elastic die deformations is essential when using an advanced friction model, especially when it is dependent on contact pressure. The presented simulations in Paper A and B would have been impossible without the correct die geometries and contact pressures. Since the physical die differed significantly from the original CAD model used in the final SMF simulation, simulations with the CAD model would not have reliably predicted geometry and contact conditions.

- A framework is suggested for a future development process of stamping dies. The desired situation is to finalize the die geometries, compensations, and tryout process as extensively as possible in a virtual environment. The connection between dies, CAD software, and numerical tools should then be maintained throughout the lifetime of the die to enable continuous production support through SMF simulations.

- The mathematical and numerical methods for surface compensations are relatively simple. However, it is of immense importance to reliably represent die and press deflections.
- Optimization techniques can be developed for production support and control, e.g., adjusting shim thicknesses to compensate for wear, process variations, or different press lines.

- Digital image correlation systems can effectively measure press and die deflections, which subsequent simulations can then utilize.

- Topology optimization can be used to inverse model press tables and the structural behavior of rams if forces and deformations are recorded together.

- The global deformations of a press line can occur on a millimeter scale during a press stroke, even if the internal deformations of the die are much smaller. If conducting surface compensation, it is vital to compensate against the correct components of the total deformation.
10 Conclusion

This chapter presents a short discussion and conclusion relating to each pair of research questions and hypotheses. The overall conclusion is that it is possible to develop efficient and reliable methods for virtual tryout and improved production support through SMF simulations that are aided by structural analysis, optimization, and process measurements. The literature has developed, demonstrated, or studied several methods to achieve this goal, and these are included in this thesis. There is seemingly a high achievable potential in the suggested and studied methods. Chapter 11 Discussion and Future Work explores challenges, possibilities, and future research questions and acts as a foundation for continuous work toward the PhD thesis in this project.

10.1 Research Question and Hypothesis 1

Hypothesis 1 was suggested as an answer to Research Question 1.

H1: The deflection of presses can be recorded with DIC systems and then be inverse modeled in FE software with methods such as super elements, modal reduction, optimization techniques, or spring systems.

RQ1: How can FE simulations reliably represent the deflection of presses and stamping dies?

The results confirm H1. Even if this research has not yet conducted a full characterization of a press, Paper D demonstrates that it is possible to measure the stiffness and deformations of a press with an ARAMIS DIC system and to inverse model the press through topology optimization with software such as Optistruct. An inverse modeled press structure should be possible to include in SMF simulations that contain 3D tool geometries in software such as LS Dyna or used to yield deformed 2D surface geometries for the strategy for inclusion of die deformations described in Paper B, e.g. in AutoForm. Scientific literature has also described various methods for press measurements, press characterization, and model reduction, e.g. [2] and [16].

10.2 Research Question and Hypothesis 2

Hypothesis 2 was suggested as an answer to Research Question 2.

H2: Virtual rework of die surfaces is proven on small experimental dies. It can therefore be performed on industrial dies as well. It will be crucial to use efficient modeling techniques and to include process parameters such as press and die elasticity. However, the elastic behavior of presses and dies must first be reliably modeled.

RQ2: How can virtual rework be used to shorten and support the tryout phase of a stamping die?
The research findings confirm H2. The methods in Paper C together with insights from previous literature reveal that it is relatively easy to compensate the surfaces in FE models of dies based on predicted deformations. However, it is imperative to model both the die deformations and press deformations in a reliable way in order for the virtual tryout to yield acceptable accuracy. Papers B and D describe the importance and characteristics of these deformations. Additionally, Paper A indicates that a correct estimation of the lubrication system is essential for SMF simulations, and a physically based model is preferable for predicting the friction conditions in the physical die. Correct die and press deformations are critical to base a pressure dependent friction model on the right contact pressure. Further research is needed to enable a full virtual tryout process; Chapter 11 Discussion and Future Work discusses this in greater depth.

10.3 Research Question and Hypothesis 3
Hypothesis 3 was suggested as an answer to Research Question 3.

H3: Industrial dies in production can be analyzed similarly to dies in the development phase. However, the analysis must include the shape of the forming surfaces, which is often different compared to the simulations before die tryout. Scanning the forming surfaces and including the geometry in the FE models can achieve this.

RQ3: How can structural FE analysis of stamping dies and press lines improve production support from SMF simulations?

The results confirm H3. Paper B outlines a method for the inclusion of die deformations in AutoForm SMF simulations of an existing die. The final geometries of the forming surfaces are their shapes immediately after blankholder closing. It is likely a drawback that the geometries are locked in one shape throughout the forming operation, even if it does improve the results considerably compared to excluding the die deformations. Further research is needed to establish the advantages and disadvantages of the suggested method in Paper B. This work will involve a comparison of the developed method to other similar simulation techniques, e.g. inclusion of the entire 3D die geometry in SMF simulations; Chapter 11 Discussion and Future Work elaborates on this insight.

10.4 Research Question and Hypothesis 4
Hypothesis 4 was suggested as an answer to Research Question 4.

H4: The literature has suggested several methods, the most promising of which are modal reduction techniques. It will be possible to use these on industrial dies in FE software where 3D elements are available. In simulations using only 2D surfaces, the deformations can be approximated by deforming a die in a 3D model and then transferring the deformed surface shapes to the 2D model.
RQ4: How can the simulation time be maintained at a reasonable level for industrial dies when the SMF simulation includes elastic die and press simulations?

The findings confirm H4 on the basis of Paper B applying and demonstrating the suggested method in H4. The literature survey also confirms the availability of other methods, such as modal reduction techniques. Chapter 11 Discussion and Future Work addresses the topic in more detail.
11 Discussion and Future Work

The following discussion and questions are recommendations for the formulation of research questions and hypotheses in continued research toward a PhD thesis. The proposed questions and their solutions can benefit the SMF industry, which will gain important tools for reducing lead time and improving production support. Additional academic and theoretical work is necessary in order to fulfil the objectives of the research project.

Both this work and previous research have verified that it is possible to run SMF simulations while considering die structures, either through full or reduced inclusion of the 3D die geometry in the SMF analysis. Sheet metal forming models that includes elastic die and press deformations, together with DIC measurements, can be a valuable tool in everything from creating simple guidelines for die manufacturing to performing full virtual tryouts and creating virtual twins of existing press lines and stamping dies. The numerical methods for compensating and optimizing die structures are also relatively efficient, e.g. compensating die surfaces against die and press deformations is numerically quite simple and fast as long as the deformations are small and linear, as described in Paper C.

It is, however, of key importance to model press elasticity and forming surfaces correctly and in detail. Any inaccuracies in geometries, boundary conditions, or elasticity can result in the FE models losing their physical meaning. To enable a robust virtual tryout and extensive virtual production support, future research should focus on press measurements as well as how to represent the elasticity in numerical simulations. For production support, it is also vital to find a fast and accurate method for including scanned die geometries in SMF and structural simulations.

The majority of SMF simulations in the foreseeable future will probably be conducted with 2D surfaces. This is also one of the main limitations within the field of SMF research. Paper B describes a method for including die deformations in SMF simulations in such 2D simulations. The method is based on scanned 2D data, deformations by structural analysis, and the export of a resulting geometry to the SMF simulations. The subsequent SMF simulations consider the deformed geometries as rigid surfaces. This represents a single point in time and thereby misses continuous die deformations throughout the SMF simulation.

When simulating an existing stamping die as in Paper B:

- What is a reliable and efficient approach for coupling or attaching scanned data of forming surfaces to the geometry or mesh in FE models?

The most obvious two tracks are CAD- or FE-based editing of the die geometries, which entail either editing the geometry directly or editing or connecting the scanned data to the FE mesh with tools such as contact algorithms or morphing.
The simulations in Paper B improved the accuracy of SMF simulations by including the elasticity of the die and an advanced friction model. There are still areas on the door panel that are over and under predicted. Possible reasons for this is non-linearities in the die structure that is missing in the FE model, missing material data such as strain rate dependency, and lack of continuous die deformations throughout the forming operation. The inaccuracies in Paper B yields the following questions:

- What are the main causes for the inaccuracies seen in Paper B?
- What are the limitations of the method presented in Paper B compared to a full inclusion of 3D die geometries in SMF simulations?
- Is there a way to extend the method used in Paper B based on meta-modeling or by using or developing the different binder models in AutoForm?

Meta models should be able to capture at least the macro deformations during the forming operation, even if a full tool geometry is unavailable. Micro deformations will require a more detailed geometry of the analyzed stamping die. Simplified models carries the risk of missing non-linearities or boundary conditions in the forming process, e.g. losing contact between cushion pins and the press cushions, see paper B. It would be interesting to compare the AutoForm simulation in Paper B to a simulation with a full discretization of the stamping die and the press and at the same time study the following question:

- What is the best method for building robust, fast, and nimble FE models that include elasticity of press lines and stamping dies on an industrial scale.

Not many models of industrial scale are demonstrated in the literature. The best way will probably be to use a combination of reduced FE models, coupling of simulation software, meta models, and full discretization with coarse and fine mesh densities that are connected with contact constraints and boundary conditions, see [2] and [8]. An important factor apart from the solver time and accuracy is the effort and time for pre-processing used in the different strategies.

Future research should investigate how to best couple the measurements with the FE model and explore other strategies and methods for measuring press characteristics. A relatively common method in the literature is to build virtual press models with springs, dampers and masses coupled with rigid or deformable solid bodies. However, full virtual representations of presses are very rare and measurements are needed to verify and monitor them during their lifetime. Digital image correlation together with structural optimization can probably be used on their own or together with other methods from the literature to build virtual presses.
It is possible to measure press deformations with DIC systems and inverse model the elastic behavior of press structures based on the acquired data. The demonstrated methods are relatively time consuming and not standardized. A future challenge is to develop a best practice for inverse modeling press parts through optimization, which includes both work with optimization algorithms and setting up efficient and reliable chains of simulations to run during the optimization procedure.

Press cushions are difficult to see with DIC systems and can be challenging to connect to any physical measurement device. However, models of the press elasticity must include them. The invisibility of press cushions for any DIC systems necessitates certain extensions through the holes in press tables or inverse modeling of the part based on indirect measurements on stamping dies.

During future press measurements the following questions should be considered:

- What is the most efficient way to set up and couple experimental DIC data with the numerical model used for inverse modeling of the press?
- Can techniques other than DIC be useful to improve the current measurements?
- How should the measured data be post-processed?
- How can scripting and optimization be applied?
- Is there an efficient method to measure and characterize press cushions?

The area of model-based control of SMF processes is experiencing a rapid growth in interest and amount of research. Paper C reveals a potential for controlling and studying adjustment mechanisms in stamping dies through optimization. This optimization was effective but slow and will require further in-depth examination of meta-models and improvement in speed if similar solutions should be implemented. The models must be coupled with control systems in production. An important question to ask, from [32], is

- “What has to be computed accurately in order to efficiently design control systems?”

The research is currently limited to SMF simulation and processes. The methods and tools in this study could also be of interest for other manufacturing processes. All manufacturing processes that involve deformation of tools and machines could be measured and included in production simulations. Hemming processes [3] is a related manufacturing area to which the findings of this work are applicable, especially since such processes are often simulated in software that is identical or similar to SMF. Since future work will include optimization, it can also be applicable in other related industrial and academic areas, e.g. many steps within material characterization is presently inverse modeled or performed similarly to programmable algorithms. The process is likely to always include human
knowledge and guidance, but certain steps can probably be optimized. Digital image correlation is also used, so there is potential synergy within at least two areas.
12 References


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. 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.
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.

![1. TriboForm Analyzer](image1.png) ![2. TriboForm FEM Plug-In](image2.png) ![3. Stamping simulation](image3.png)

**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 $\tau_{\text{asp}}$ 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 $p_{\text{hub}}$ (i.e. the load carrying capacity of the lubricant). To solve $p_{\text{hub}}$, 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 $\tau_{\text{hub}}$ is calculated based on the obtained hydrodynamic pressure distribution. The summation of the shear stress acting between contacting surface asperities $\tau_{\text{asp}}$ and the shear stress acting at the fluid–solid interface $\tau_{\text{hub}}$ is used to obtain the desired coefficient of friction $\mu$, see Equation 1.
The aim of this work is to account for realistic friction and lubrication conditions in order to improve the simulation accuracy and enable the detection and prevention of tribology related quality issues in the virtual design process.

\[ \mu = \frac{T_{\text{app}} + T_{\text{trib}}}{P_{\text{norm}}} \]  

(1)

2.2. Friction model
The TriboForm software calculates 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.

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.

| $\sigma_0$ | $\sigma_{45}$ | $\sigma_{90}$ | $\sigma_b$ | $R_0$ | $R_{45}$ | $R_{90}$ | $R_b$ | $M$  |
| [MPa]     | [MPa]         | [MPa]         | [MPa]     |       |         |         |       |     |
| 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/m² and 2.2 g/m² at different locations on both sides of the sheet. An average value of 2.0 g/m² 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.
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).](image)

![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)](image)

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\textsuperscript{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\textsuperscript{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.
The part shape after forming is displayed in Figure 8. With a constant friction coefficient of \( \mu = 0.15 \) 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.

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
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References
Introduction of elastic die deformations in sheet metal forming simulations

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A B S T R A C T

Simulations of sheet metal forming (SMF) with finite element models (FE-models) for stamped parts in the car industry are useful for detecting and solving forming problems. However, there are several issues that are challenging to analyze. Virtual tryout and analyzes of stamping dies in running production are two important cases where many of these challenging issues are present. Elastic deformations of dies and press lines and a physically based friction model is often missing when these types of cases are analyzed. To address this, this research aims to develop a method wherein the results of two separate FE-models are combined to enable SMF simulations with the inclusion of elastic tool and press deformations. The two FE-models are one SMF model with two-dimensional (2D) rigid tool surfaces and one structural model of the die and press. The structural model can predict surface shapes and pressure distributions for a loaded stamping die. It can also visualize relatively large and unexpected deformations of the die structure. The recommended method of transferring the deformations from the structural model to the 2D surfaces is through an FE technique called submodeling. The subsequent SMF simulations show that the method for calculating and using the deformed surfaces together with the TriboForm friction model yields a result that matches measured draw-in and strains. It is verified that the ability to virtually deform a die and include the resulting geometry in forming simulations is of high importance. It can be used for the virtual tryout and optimization of new dies or analyses of existing dies in running production. It is suggested that future research focus on a more efficient and automated workflow. More experimental data and simulations are also needed to verify the assumptions made for the simulation models. This will enable the method to be adopted in a reliable way for standard SMF simulations.

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1. Introduction

Simulations of SMF with FE-models for stamped parts in the car industry are useful for detecting and solving forming problems. However, there are several issues that are challenging to analyze. Virtual tryout and analyzes of stamping dies in running production are two important cases where many of these challenging issues are present. Elastic deformations of dies and press lines and a physically based friction model is often missing when these types of cases are analyzed.

A correct representation of the forming surfaces in a stamping die is key for SMF simulations. 2D rigid representations of the nominal surfaces are normally used during the development phase of a die. However, if a virtual tryout or an analysis of an existing die is performed, it is vital to include both the shape of the real physical surfaces and the elastic behavior of the die and the press line. Scanning tool surfaces is one way to obtain data for SMF simulations, which was the one used in this research. The work in this paper was done in cooperation with a project by the commercial software TriboForm, which was used to study and create friction models for the simulations in this research (Sigvant et al., 2015, 2016a,b; Hol, 2013). This friction study was performed through experiments and simulations of the formation operation of the existing die for the XC90 rear door inner, shown in Fig. 1.1. It is common knowledge in the field of SMF simulations that die and press deformations influence the stamping process. It is crucial to represent these deformations in SMF simulations, both for accurate shape representation and correct prediction of contact conditions, which influence the friction model. These deformations are difficult.

Abbreviations: SMF, sheet metal forming; FE-models, finite element models; AutoForm, AutoForm\textsuperscript{TM} R6.0; 3D, three-dimensional; 2D, two-dimensional; Volvo, Volvo Cars; Hypermesh, Hypermesh 13.0; ABAQUS, ABAQUS 6.14; stl, stereolithography; CAD, computer-aided design.
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to predict in standard SMF simulations where the forming surfaces are represented as 2D rigid surfaces and the SMF software is often not capable of performing 3D structural modeling.

Previous work has been done regarding elastic tool deformations and their influence on the forming process and simulations. One example, which is one of the most extensive works in the area of combining structural behavior and SMF simulations, by R.A. Lingbeek, describes different methods for analysis and virtual rework of tool structures and surfaces (Lingbeek, 2008). Another example (Grofmann et al., 2008) outlines a method for compensating against elastic tool deformations and demonstrates it through simulations. Most previous work in the area of combining structural analysis and SMF simulations has been performed on small industrial or experimental dies. Several studies assert that more work is required, especially simulations and validations for dies on an industrial scale. Many suggested methods combine the structural analysis and forming simulation into one FE-model. This leads to large models, which are time-consuming to solve when scaled to dies on an industrial scale. A couple of suggested methods to reduce the degrees of freedom in a combined FE-model is coupling of coarse and fine meshes or an approach called static condensation (Haufe et al., 2008). Methods of reduction are not possible in most widely-used SMF software, such as AutoForm, which currently offer no possibility to include solid structures. All methods for reduction of structural models have advantages and disadvantages, since some information and accuracy is always lost. Software for structural analysis are also generally not developed for advanced SMF-simulations. AutoForm, which is used for the SMF simulations in this paper, has some simplified capabilities for modeling the blankholder deformations through its different binder models. These binder models are not independent on any real die geometry and the surfaces in the models are not really deforming. It is instead the contact conditions that are controlled to simulate the effect of the deforming structure. The user of AutoForm gives input corresponding to die dimensions such as width, length and height together with stiffness values for the die and contact algorithm. The input can also include the positions of cushion pins and gas springs. All these parameters will impact the contact conditions for the die surfaces.

To address the presented issues, the aim and focus of this research is to develop and discuss a method wherein two separate FE-models are combined to enable SMF simulations that include the elastic deformations of stamping dies and press lines. One model, solved in the software ABAQUS, is for structural analysis of the die and press deformations. The other model is for the SMF simulations with AutoForm. Information will be transferred from the structural model to the SMF model in order to achieve reliable simulation results. This method has two benefits. The first is the potential for die and press deformations to be incorporated into SMF software without the possibility to model 3D solids. The second is its ability to reduce solver time when SMF and structural behavior must be simultaneously analyzed, see (Pilthammar et al., 2016).

Previously, Volvo has also conducted research on structural analysis and optimization of stamping dies. Two master theses were performed at Volvo Cars: one in 2007, summarized in a conference paper (Nilsson and Birath, 2007), and one in 2016 (Reddy and Tatinpala, 2016). Both theses indicated a high potential for improving die designs by using structural analysis and other numerical tools.

The research question in this paper is to investigate and develop a method for combining a structural FE-model and a SMF simulation model. This is achieved by transferring information about the structural behavior of the die and press line from the structural FE-model into the SMF model. When used together, the two models yield a total solving time that is significantly shorter than that of a model which combines structural analysis and forming simulation. An accurate and fast method is vital if used for virtual tryout or for analyses of real dies in running production. This method is valid under certain assumptions, presented in Section 2.

This article is organized into five chapters. Section 1 is an introduction to the research question and its context. Section 2 presents the experimental and simulation methods together with a more thorough background on the theory and assumptions that this research is based upon. Section 3 presents the results from the models used in the different simulations. Section 4 is a discussion about the methods and the results. Section 5 presents the conclusions of the research and suggestions for follow-up research.

2. Experimental and simulation methods

This chapter presents experimental data from a production run of the XC90 rear door inner. It also describes the theoretical background, assumptions and setup for the different numerical methods and FE-models used for analyzing the forming procedure of the stamping die.

2.1. Full-scale production run

A production run with the XC90 rear door inner was enacted in order to gather data for the following simulations. The press was a mechanical transfer press line at Volvo Cars in Olofström, Sweden. The velocity profile was recorded for use in the TriboForm friction model during forming simulations.

The die material was GGG70L, with a die and punch that were chrome plated in selected areas. The forming surfaces of the blankholder were polished and laser hardened. The geometries of the forming surfaces were scanned. The blank material was VDA239-C34 GL, with a thickness of 0.7 mm and Fuchs 4107 as prelube. Measurement of the lubrication amount in the production indicated a variance between 0.7 g/m² and 2.2 g/m² across the blank.

Some collected data, from the production run, is presented in Figs. 2.1–2.4. Fig. 2.1 shows a spotting image. Spotting is a technique wherein the metal sheet is painted before the die is closed – in this case, the blankholder and matrix are painted in the areas where contact is expected when the blankholder is closed. When the tool is opened, the paint is removed where there is pressure caused by contact between the sheet and the tool surfaces. Figs. 2.2 and 2.3 are showing the scanned outline and strains measured...
Fig. 2.1. Spotting of the blank.

Fig. 2.2. Scanned outline of the drawn blank.

Fig. 2.3. Strain measurements with Arqus. Major strain is plotted in the figure.

Fig. 2.4. Distance between scanned blankholder and scanned matrix in unloaded condition.

on a real formed sheet. Fig. 2.4 demonstrates that the distance between the blankholder and the matrix exceeds two sheet thicknesses in some areas when the die is unloaded. This distance is expected to be close to 0.7 mm which is the blank thickness and the distance in the original CAD-model of the die. The surfaces are positioned for this measurement such that the closest distance between them is 0.7 mm, corresponding to the blank thickness. This measurement is based on scanned data of the die surfaces obtained with Atos/GOM compact scan together with the software Atos Professional V7.5 SR1. The alignment of the scanned surfaces was made with a Canon EOS 1D with the software Tritop Professional V7.5 SR1.

2.2. Structural analysis of the stamping die

Since the gap between the surfaces of the matrix and the blankholder differs significantly, it is assumed that this distance will vary when the die is loaded. Therefore, it is necessary to virtually deform the surfaces before they can be used in a forming simulation. The aim of the structural analysis is to replicate the shapes of the blankholder and matrix surfaces at a single point in time, when the blankholder is closed before the forming has started. This is the same position as in the spotting image in Fig. 2.1. The calculated shapes of the surfaces are then used in forming simulations. The reason for choosing this point in time is that it represents the most common position used at Volvo for spotting of the blankholder.

Using the deformed surfaces from the structural model in a forming simulation is valid under the assumption that the change in tool deformations is relatively small after the blankholder has been closed. Additional deformation should be manageable using functions as the various support types in AutoForm, which are approximations or metamodels of how a die deforms.

In order to virtually deform the tool surfaces, a structural FE-model of the die was created in Hypermesh and solved with ABAQUS. The die was modeled as elastic bodies and solved with a dynamic quasi-static method. The ram was assumed to be rigid and an elastic model of the cushion was included in the model. The cushion force, measured in the real press line, was applied at the points where the cylinders connected to the cushion. The lower shoe and the punch was excluded since it has no influence on the deformations of the die in the calculated position.

No metal sheet is present in the structural model; instead, the sheet is represented by a contact surface which was given the same thickness as the sheet: 0.7 mm. No forming is done in this model because the desired result is the shape and behavior of
the moment when the blankholder is closed. Although the shape is correct, it is not possible to create a surface based on the solid mesh and use it in AutoForm. This is because the structural mesh is too coarse for use in AutoForm for SMF. It has to be coarse for a reasonable solving time of the solid model. A solution is to use the scanned surfaces, which have meshes that are sufficiently fine, and deform those surfaces based on the deformations from the structural model. Two different strategies have been used: morphing in AutoForm and submodeling in ABAQUS.

2.3.1. Deforming the scanned surfaces by morphing in AutoForm

In AutoForm, morphing is done by using guide curves. These guide curves describe the parameters of where the surfaces should be morphed. Catia V5 was used to create guide curves on the original scan surfaces and on the deformed surfaces from the structural FE-simulation. The curves are identically positioned in the xy-plane; the only difference is the curvature in the z-direction. The position of the curves on the blankholder are depicted in Fig. 2.7. Because the distance between the curves is minute, it is difficult to identify that there are two sets of curves in Fig. 2.7. These curves are created to cover the deformation of the entire blankholder surface.

2.3.2. Deforming the scanned surfaces by submodeling in ABAQUS

Submodeling is a method that applies a variable, such as the deformations, from one structural model as a load or boundary condition to a second model (ABAQUS). It is often used to apply deformations from a large global model as boundary conditions to a smaller part of the model that is of high interest and modeled in greater detail in the submodel. In this work, the method is instead used for applying the deformations from the 3D model of the stamping die to the scanned 2D surface of the die surfaces. The scanned 2D surfaces are triangulated surfaces representations in stl-format and are therefore possible to import into most FE-software for use as a mesh in an analysis. Fig. 2.8 shows the deformations transferred from the structural model to the scanned stl-surface.

2.4. SMF simulations

The forming simulations are performed in AutoForm with different configurations for seven models labeled A-G. The different configurations includes deformed surfaces and the original scanned surfaces, the velocity of the press, the TriboForm friction model and constant friction. By using this input, the shape of the physical die and lubrication system is represented in different ways in the SMF simulations. The configuration for each model is presented in Sections 2.4.1–2.4.7. Simulation model A is chosen as reference because it is using the TriboForm friction model, the surfaces are
Table 2.1. Material parameters used in the BBC2005 material model.

<table>
<thead>
<tr>
<th>$\sigma_0$ (MPa)</th>
<th>$\sigma_{01}$ (MPa)</th>
<th>$\sigma_{02}$ (MPa)</th>
<th>$\sigma_{03}$ (MPa)</th>
<th>$R_0$</th>
<th>$R_{25}$</th>
<th>$R_{45}$</th>
<th>$R_{65}$</th>
<th>$m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>156.6</td>
<td>160.0</td>
<td>156.0</td>
<td>187.0</td>
<td>1.81</td>
<td>1.34</td>
<td>1.88</td>
<td>0.98</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Fig. 2.8. Deformation of the matrix in the solid model (upper) and deformation of the scanned matrix in the submodel (lower) (mm).

Fig. 2.9. Hardening curve used in the BBC2005 material model.

Fig. 2.10. Forming limit curve at onset of localization used in the SMF simulations.

2.4.1. Model A: simulation with compensated surfaces (submodeling) and TribоФorm friction model (reference simulation)

The following simulation parameters are used in AutoForm:
- Tool surfaces: Tool surfaces are compensated for the elastic deformation by submodeling in ABAQUS
- Friction: TribоФorm friction model
- Support type for blank holder: Force controlled with uniform loading condition
- Tool stiffness: 5000 MPa/mm

2.4.2. Model B: simulation with uncompensated scanned surfaces

Difference from reference simulation model A in Section 2.4.1:
- Original scanned surfaces without any type of surface compensation.

2.4.3. Model C: simulation with compensated surfaces (morphing)

Difference from reference simulation model A in Section 2.4.1:
- Tool surfaces are compensated for by morphing in AutoForm.

2.4.4. Model D: simulation with lower tool stiffness: 100 MPa/mm

Difference from reference simulation model A in Section 2.4.1:
- Tool stiffness: 100 MPa/mm (instead of 5000 MPa/mm)

2.4.5. Model E: simulation with higher tool stiffness: 15,000 MPa/mm

Difference from reference simulation model A in Section 2.4.1:
- Tool stiffness: 15,000 MPa/mm (instead of 5000 MPa/mm)

2.4.6. Model F: simulation with constant friction of 0.12

Difference from reference simulation model A in Section 2.4.1:
- Friction coefficient: 0.12 (instead of TribоФorm model)

2.4.7. Model G: simulation with constant friction of 0.15

Difference from reference simulation model A in Section 2.4.1:
- Friction coefficient: 0.15 (instead of TribоФorm model)

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2.5. TriboForm friction model

The TriboForm software is used together with experimental data to create a physically-based friction model that is used in most of the following forming simulations. In this case, the friction model is 3D and depends on contact pressure, relative sliding velocity, and plastic strain in the sheet material (Sigvant et al., 2016a).

A constant friction can often produce reliable results. However, constant friction must be inversely modeled by studying the output from a real die or applied with extensive experience of which friction coefficient to use for many different lubrication systems. Therefore, one of the main reasons for a physically-based friction model is to predict the friction conditions in a simulation before a die is manufactured.

The TriboForm software is based on the research presented in Hol (2013). The creation of each friction model starts with defining a tribological system, i.e. a sheet material with or without coating, a lubricant and a tool material with or without coating and hardening. The input to the model are the mechanical properties for the sheet material, the surface roughness of both the sheet and the die surfaces, together with the viscosity and amount of lubricant. Each model is then calibrated with rotational friction tests and a library is created for the tribological system. The software TriboForm Analyzer reads the library and the user can easily change the surface roughness for the sheet and the die as well as the amount of lubrication. It is possible to visualize both the selected surfaces and the resulting friction model, see Figs. 2.12–2.13. When the user is satisfied with the settings, a file containing information about the defined friction model is exported to AutoForm for use in SMF simulation. This process and a more in-depth description of the creation of the specific model used in these simulations is described in (Sigvant et al., 2015, 2016a,b; Hol, 2013).

3. Results

This chapter contains the results from the different methods and models used in the research. It describes the results from the structural FE-model of the stamping die, how the results were transferred to the SMF model and the final results from the SMF model itself.

3.1. Structural analysis

Sections 3.1.1–3.1.3 present the results from the structural analysis of the stamping die. The loadstep for the deformation of the
die is solved in 15 h on 64 cores. The convergence of the contact problem consumes the vast majority of the solver time. This is because the mesh is coarse and based on scanned data. Reduction of the solver time is discussed in Section 5.2.

3.1.1. Deformations
The deformations of the matrix and the blankholder are shown in Figs. 3.1 and 3.2. The legend for the deformation of the blankholder does not start at zero due to some rigid body motion in the model prior to contact with the matrix. In Fig. 3.3, the deformation is magnified 250X and shows that the blankholder bends in an arc shape. The deformation of the blankholder is significantly larger than the deformation of the matrix, even when the rigid body motion is neglected for the blankholder.

3.1.2. Contact between cushion pins and cushion
Since the blankholder bends upwards, many of the cushion pins lose contact with the cushion. This is visible in Fig. 3.4.

3.1.3. Virtual visualization of the spotting
Visualization of the spotting is facilitated by setting the values to appropriate levels for the variable COPEN in ABAQUS. COPEN represents the distance between the slave and master contact surfaces in the structural analysis. The variable COPEN or contact pressure are both variables that are possible to use for a virtual spotting image. The values in the color legend are identified simply by attempting different combinations. This reveals the potential to predict and compare the contact surface with real photos. However, the full contact area in the structural model will not have a perfect match with the real spotting image, because areas in contact with a low pressure will leave the paint intact. Further research is therefore necessary to determine how to set the values in the legend for a robust and reliable comparison. The values should be based on experimental data for a number of dies compared with simulations. A comparison of the virtual and real spotting is visualized in Fig. 3.5.

3.2. Modification of the scanned surfaces
Figs 3.6-3.8 visualize the resulting geometries with the morphing and submodeling methods, used for transferring the structural deformations from the structural FE-model in ABAQUS to the SMF model in AutoForm. The morphing and submodeling are based on the deformations predicted by the structural model.

3.3. Results of SMF simulations
This chapter presents the results from seven SMF simulations conducted in this research. Results are presented for the models, labeled A-G, in Sections 3.3.1-3.3.9. The SMF simulation models is solved in 3 h on 8 cores.

Fig. 3.9-3.15 in Section 3.3.8 are visualizing the difference between the simulated part and the scanned outline of a real part for each model. The figures depict the geometries from each SMF simulation together with a scanned draw-in curve from a real part.

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Figs. 3.6-3.22 in Section 3.3.9 shows the difference between the SMF simulations predicted major strain and the experimental one, for model A-G. Red and black indicates over-prediction while blue and white indicates under-prediction.

The results for model A in Section 3.3.1 are the most reliable of all the forming simulations and includes both compensated tool surfaces and the TriboForm friction model. Therefore, these results are used as a reference point for comparison with the rest of the simulations presented in this article. Model C in Section 3.3.3 yields very similar results. However, model C is not chosen as reference since its surfaces were compensated by morphing in AutoForm instead of submodeling in ABAQUS. There are potential issues with the morphing method that are visualized in Section 3.2 and discussed in Section 4.2.

The parameters changed with respect to the reference simulation model A are stated in the title of each Sections 3.3.1–3.3.7 and more in detail in Sections 2.4.1–2.4.7.

The importance of being able to virtually deform and use surfaces with a correct shape in SMF simulations is also necessitated by the inability to obtain satisfying results when using the original scanned surfaces in AutoForm. The best achievable results with
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3.3.4. Model D: simulation with lower tool stiffness: 100 MPa/mm
The predicted draw-in is under-predicted in several areas when compared to the reference model A. There is also significant over-prediction of the strains.

3.3.5. Model E: simulation with higher tool stiffness: 15,000 MPa/mm
The predicted draw-in is similar to the reference simulation model A. The strains are also similar, except for some over-prediction in minor areas.

3.3.6. Model F: simulation with constant friction of 0.12
The draw-in is similar to the reference simulation model A. The strains are also similar, excluding some minor areas that are over-predicted compared to the reference simulation.

3.3.7. Model G: simulation with constant friction of 0.15
The draw-in is under-predicted in several areas compared to the reference model A. There is also significant over-prediction of the strains.

3.3.8. Draw-in comparison for model A–G
3.3.9. Over- and under-prediction of major strain for model A–G

4. Discussion
This chapter is a discussion of the methods and results presented in this paper.

4.1. Discussion of structural analysis
The structural model is a relatively simple linear elastic FE-model. This model can accurately predict the surface shapes and pressure distributions. This is indicated by the fact that the initial gap between the die surfaces is closed and that the use of the resulting surfaces in SMF simulations yields reliable results close to real measurements. However, the results are somewhat unexpected. The large deformations of the blankholder and the loss of contact between the pins and the cushion are not the desired behavior for a stamping die. According to the results, it will be difficult to obtain a satisfactory blankholder pressure on some areas of the blankholder surface. This has been confirmed by individuals working with the real die at Volvo. One element missing in the model is the elastic behavior of the ram. No full CAD model or drawing is available, so including it in the model requires the

Fig. 2.15. Model G: SMF simulation compared to scanned outline of real part.

Fig. 2.16. Model A: over- and under-prediction of first major strain. (For interpretation of the references to color in the text, the reader is referred to the web version of this article.)

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Fig. 3.17. Model B: over- and under-prediction of first major strain. (For interpretation of the references to color in the text, the reader is referred to the web version of this article.)

Fig. 3.18. Model C: over- and under-prediction of first major strain. (For interpretation of the references to color in the text, the reader is referred to the web version of this article.)

Fig. 3.19. Model D: over- and under-prediction of first major strain. (For interpretation of the references to color in the text, the reader is referred to the web version of this article.)

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Fig. 3.20. Model E: over- and under-prediction of first major strain. (For interpretation of the references to color in the text, the reader is referred to the web version of this article.)

Fig. 3.21. Model F: over- and under-prediction of first major strain. (For interpretation of the references to color in the text, the reader is referred to the web version of this article.)

Fig. 3.22. Model G: over- and under-prediction of first major strain. (For interpretation of the references to color in the text, the reader is referred to the web version of this article.)

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deformations of the ram to be characterized and represented in the model through other means. Likely, the best approach is to use certain deformation measurements. In this specific case, it is expected that the influence of the extra deformation of the ram will be minor, since the deformation of the blankholder is large and will therefore govern the resulting pressure distribution. The model also indicates a possibility to visualize the spottings in a virtual environment. More experience is needed for the values used in the color legend in order to represent it correctly.

It is likely possible to avoid the problems visualized for this die. Numerically, this can occur by making a structural optimization of the solid structure and performing a virtual spotting of the die surfaces before the die is manufactured.

4.2. Modification of the scanned surfaces

Both methods presented in this paper perform effectively in moving the deformations from the structural model to the SMF model. The recommended method is submodeling because it transfers the exact deformation field from the global model to the submodel. Furthermore, it can be scripted and automatized to run directly after the global structural model is solved. This requires no extra manual work beyond the import into AutoForm.

The morphing method needs manual post-processing and includes an extra step in CAD software before the guide curves can be imported into AutoForm. In AutoForm, the surfaces must be morphed by the guide curves in an additional operation. The morphing is also problematic with advanced surfaces, as evidenced in the results from the morphing of the matrix in Fig. 3.7. The resulting deformations look abnormal, while the morphing of the simpler blankholder effectively resembles the surface modified by submodeling. The influence of the unsuccessful morphing of the matrix on the final results is likely of minimal significance since the absolute deformation of the matrix was so small compared to the blankholder.

4.3. Discussion of SMF simulations

The simulations presented in this paper show that the method for calculating and using the deformed surfaces together with the TriboForm friction model yields reliable results, provided that friction and contact conditions are represented effectively in AutoForm.

One issue is the over-prediction of strains around the holes; this is likely due to strain rate effects. Generally, the plastic strain rates in the SMF simulations in this paper are much higher than standard simulations at Volvo Cars. The reason for this is that the real press velocity is used instead of a standard value of 1 mm/s, since the TriboForm friction model is dependent on the sliding velocity of the blank. There are areas in the part that reaches strain rates of more than 1 s⁻¹ which leads to a stronger material locally. That would lead to reduced strains in those areas if strain rate effects were to be introduced in the SMF model.

It is interesting to note that a constant friction of 0.12 produces a result equally reliable as that of the TriboForm friction model. However, the benefit of the TriboForm model is the ability to predict the friction without using inverse modeling or depending on years of experience to achieve accuracy.

For some or all dies, there will be elastic deformations of the die structure during the forming operation. It could potentially be handled by applying an average deformation based on different points in time during the drawing of the blank. Another option could be to use the presented method to correct the surface shapes when the blankholder is closed, and then investigate whether some of the support types and load conditions for the blankholder in AutoForm can account for the remaining deformations.

5. Conclusions

This chapter concludes the research presented in this paper and suggests topics for follow up research.

5.1. Conclusions about suggested methods and results

The ability to virtually deform a die and include the resulting geometry in forming simulations is of high importance. The aim of this research was to combine two simulation models to create a new strategy for including die and press deformation into SMF simulations. One example of the method has been demonstrated in this paper with successful results. The main benefit of the method is that it makes it possible to include die and press deformations in SMF simulations where the die surfaces are represented as 2D surfaces. SMF simulations with 2D surfaces is the most common simulation method, often in software without the possibility to model 3D solid structures such as AutoForm, which is used for SMF simulations in this paper. The simplified binder models implemented in AutoForm are found insufficient to represent the deformations of the forming surfaces in these simulations.

Another benefit of the method is the relatively short total simulation time of both models when compared to some other methods for incorporating die deformations, such as combining both structural and forming simulations in the same model without any type of reduction method for the degree of freedoms.

The suggested method can be used to offer support to running production or analyses of an existing die. This link between structural analysis and SMF will also enable additional methods for virtual design and rework of stamping dies. Structural optimization and methods for virtual spotting should be used together for controlling the die deformations. This would provide an optimum die design.

5.2. Follow-up research

Follow-up research is suggested in the following areas:

A more efficient workflow is needed. Currently, the total solver time of both the models is relatively short. But setting up the models has the potential to be much faster and more automated. This is crucial if the method shall be adopted in standard forming simulations. The increase in computational time when an elastic model of the die is used instead of rigid surfaces is studied in Neto et al. (2016), where it is stated that the computational time is increased by a factor of 9–14 times for the specific model in that paper. If it was possible to use the elastic die presented in this paper in AutoForm there is no doubt that the computational time would increase by a large factor for this model as well. It is probably possible to reduce the computational time substantially for the structural model by a coarsening of the elements in the main body of the die and a smoothing of the contact surfaces (Neto et al., 2017) for an increased convergence rate of the contact algorithm. Even if the computational time is reduced it is probably not enough to achieve a combined structural and SMF model that is solved in a reasonable time by just combining them. Some reduction of the models degree of freedoms would have to be used. Reduction methods are studied in Lingbeek (2008), where it is concluded that static condensation is not a reliable method to use for stamping dies, since it is accurate but it increases the computational time by a factor of 10 because many nodes have to remain on the detailed die surfaces. A promising reduction method is Deformable Rigid Bodies (DRB), which is a modal method. A reliable simulation is achieved by the DRB method with an increase of only

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8% in computational time. Since the method in this paper is suggested for software that offer no possibility to model solid structures, such as AutoForm, the different methods for reduction are not a way forward until it is possible to include solid structures in that type of software. The structural model presented in this paper could be reduced but the effort will probably not repay itself in a reduced computational time, since the structural model is only solved once in this case.

More research is needed that verifies the method on more and different types of stamping dies. The assumption that the die deformations are small after the closing of the blankholder also needs to be investigated more thorough. A suggestion is that these deformations can be handled by the different support types and blankholder models available in AutoForm. The structural analysis to obtain the correct surface shapes can also be made for other points in time during the forming operation, e.g. end of the forming operation or any other point. It is possible that any other point in time is the most crucial for good SMF simulation results, or an average of several different points.

One drawback of the friction model is that it creates one single friction model for all the forming surfaces. The simulation model has the potential to be even more accurate if separate friction models could be created for different areas and parts of the forming surfaces. This is implemented in AutoForm from version 7.1 and can be used in future work.

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Framework for Simulation-Driven Design of Stamping Dies Considering Elastic Die and Press Deformations

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Abstract. Sheet metal forming (SMF) simulations are used extensively throughout the development phase of industrial stamping dies. In these SMF simulations, the die and press are normally considered as rigid. Previous research has however shown that elastic deformation in these parts has a significant negative impact on process performance. This paper demonstrates methods for counteracting these negative effects, with a high potential for improved production support and a reduced lead time through a shorter try-out process. A structural finite element model (FE-model) of a simplified die is studied. To account for elastic deformation, the blankholder surfaces are first virtually reworked by adjusting the nodal positions on the die surfaces attaining a pressure distribution in accordance to the design phase SMF simulations with rigid surfaces. The elastic FE-model with reworked surfaces then represents a stamping die in running production. The die is now assumed to be exposed to changed process conditions giving an undesired blankholder pressure distribution. The changed process conditions could for example be due to a change of press line. An optimization routine is applied to compensate the negative effects of the new process conditions. The optimization routine uses the contact forces acting on the shims of the spacer blocks and cushion pins as optimization variables. A flexible simulation environment using MATLAB and ABAQS is used. ABAQS is executed from MATLAB and the results are automatically read back into MATLAB. The suggested optimization procedure reaches a pressure distribution very similar to the initial distribution assumed to be the optimum, and thereby verifying the method. Further research is needed for a method to transform the calculated forces in the optimization routine back to shims thicknesses. Furthermore, the optimization time is relatively long and needs to be reduced in the future for the method to reach its full potential.

INTRODUCTION

Sheet metal forming (SMF) simulations are used extensively throughout the stamping industry. It is generally applied during the development phase of stamping dies to predict results such as shape, springback, wrinkles, and different types of failure. The forming surfaces in a die are designed based on the results from the forming simulations.

Stamping dies and press lines are assumed to be rigid in most SMF simulations, both for reducing the model size and that die and press deformations often are unknown and too complex to include in the simulations. The impact on the forming process from the press- and die deformations is instead handled by manual adjustments of the forming surfaces in CAD software based on prior experience and during the try-out phase by manual rework of the forming surfaces. These two methods for compensation of die surfaces are performed by skilled experts based on experience and craftsmanship. The rework in CAD software is often performed by bending the die surfaces in a cylindrical or spherical shape to counter elastic die and press deformations. A standard procedure for a die try-out is described in Fig.1.

There is still a large potential to develop simulation support for the try-out process and other areas in the stamping industry. When SMF simulations are applied to cases such as try-out or dies in running production it is vital to consider the elastic die and press deformations. The importance of representing the physical properties, such as elastic deformations and friction modeling, is studied in previous work, see [1] and [2]. Methods to include and counteract elastic deformations of dies and press lines in SMF simulations can be used to drastically reduce the try-out time and cost. The inclusion of elastic deformations in SMF simulations will also generate an improved capability to analyze
dies in running production subjected to ever changing process conditions. This paper demonstrates one such method where it is important to consider and control the effect of the deformations of a stamping die. The study is focusing on the contact pressure distribution between a blankholder and a matrix in a single action stamping die.

FIGURE 1. Traditional design and try-out process for a stamping die.

It is assumed in this paper that altered process conditions distort the blankholder pressure distribution into an undesired state. In reality this can happen during the try-out phase or if the die is moved between press lines with different elastic behaviors. The aim of this research is to create a routine for optimization of the contact pressure distribution on the blankholder surfaces. The objective of the optimization is to yield an optimum pressure distribution of the die by optimizing the shims thicknesses of cushion pins and blankholder spacers in a die. The shims in stamping dies are used to adjust the contact pressure distribution on the blankholder surfaces by adjusting the length of blankholder spacers and cushion pins. The different parts of the die and their denotation are shown in Fig.3. This method will be most valuable when a die has reached a maturity level where it is impossible, or not allowed, to adjust the die surfaces.

The desired contact pressure in a die is predicted by SMF simulations. One of the objectives of the try-out process is to reach this predicted contact pressure. When it is reached it will yield a process very similar to what is simulated in the SMF software. The contact pressure distribution in a die varies a lot across the die surfaces, an example is shown in Fig.2. However, an even blankholder pressure distribution is selected as objective in this paper for illustrative purposes and the fact that it is easy to work with in simulation software. The aim for real blankholder pressures is also often close to evenly distributed. The pressure distribution from the SMF simulation of the specific part should be used as the objective if the method is applied in reality. The method can also be used to adjust the pressure in selected areas on the die surfaces, if it is desired during the lifetime of a die.

FIGURE 2. Contact pressure distribution in the real die for the XC90 rear door inner

METHODS

Structural FE-model

The optimization routine presented in this paper is applied on a structural model of a stamping die. The model is depicted in Fig.3.(a). Due to geometrical symmetry, a simplified finite element model (FE-model), considering only a quarter of the studied single action die, is used. Another simplification of the model is that no metal sheet is present,
there is instead a contact surface across the entire blankholder surface, a modelling technique described in [1]. These type of model simplifications are very important in order to shorten the time for each function call in the optimization routine. This is desired since the research is focusing on the optimization routine and not the structural model itself. The FE-model has 15285 degrees of freedom and consists of the blankholder with cushion pins and a matrix. The blankholder and matrix are modeled as grey iron with a Young’s modulus of 103 GPa and a Poisson’s ratio of 0.26. The cushion pins are modeled as steel with a Young’s modulus of 210 GPa and a Poisson’s ratio of 0.35. The contact between the Matrix and the Blankholder is modeled with Abaqus General Contact Algorithm with default settings.

The blankholder surfaces are completely flat in the original CAD-model and the ram in the press is assumed to be rigid. The press is omitted in the model and instead represented by several forces acting on each of the cushion pins. The blankholder spacers are represented by force pairs acting on the blankholder and the matrix.

The use of forces instead of contact surfaces between die, press, and blankholder spacers is mainly used to prevent non-linearities in the optimization routine. Non-linearities will happen if bodies go in and out of contact with each other, the use of forces in the FE-model will instead give continuous adjustments of the calculated contact forces. The magnitude of the forces acting on the cushion pins is 50.0 kN, and 2.0 kN on the blankholder spacers.

**FIGURE 3.** (a) Structural FE-model (b) Pressure Distribution (max 6.37 MPa)

The resulting FE-model is solved very fast, as desired, with ABAQUS 6.14 (ABAQUS) [3] and yields the pressure distribution in Fig.3.(b) which is very uneven. This is similar to the situation when a new die is mounted and loaded in a press line for the very first time. Manual rework, spotting, of the die surfaces is then traditionally performed to achieve the desired pressure distribution (see workflow outlined in Fig.1.). In the suggested framework the surfaces are virtually modified before manufacturing of the physical die, reducing resource consuming manual rework.

**Virtual rework of the die surfaces**

**FIGURE 4.** (a) Distance between original and reworked blankholder surface (b) Contact pressure distribution in the FE-model with reworked die surfaces.
A method for virtual rework of die surfaces is presented in [4]. A slightly modified version of this method is adopted and incorporated in the suggested workflow for how to account for elastic deformations in die design presented in this paper. Both the blankholder and the matrix surfaces are reworked by applying or mapping the desired pressure distribution to the die surfaces in separate FE-models. The surface nodes of the blankholder and the matrix are then compensated based on the calculated deformations of the FE-model. Basically the method consists of moving the surface nodes on the undeformed model the same distance as they are displaced in the opposite direction due to the applied pressure distribution. An in-house code written in MATLAB 2011b (MATLAB) [5] automates this compensation procedure. The process has to be iterated a few times since the stiffness of the structure is altered when the geometry is changed by the nodal compensation. The reworked mesh is finally imported into the original FE-model of the complete die. Adjustment of CAD surfaces based on the FE-results is also needed during the development of real dies. Figure 4.(a) is visualizing how much the surface of the blankholder was compensated and Fig. 4.(b) is showing the resulting pressure distribution in the full FE-model with the reworked mesh.

Optimization

The model from the previous subchapter with reworked surfaces represents a new die just after the try-out process is finished. During its lifetime it will be subjected to continuously changing process conditions such as different press lines, wear, variations in sheet material properties, and different force levels. The aim of the optimization part in this paper is a routine that is adjusting the process parameters for a die in operation to counteract the negative effects of changing process conditions and thereby render a desired contact pressure distribution. The even pressure distribution of the FE-model with the reworked surfaces in Fig.4.(b) is chosen as the objective. Rational for using an even pressure distribution as objective is discussed in the chapter “Introduction” of this paper.

The routine starts out from an non-optimal pressure distribution, exemplified in Fig.5.(a), achieved by changing the values of the forces acting on the cushion pins of the blankholder spacers. Changing the forces acting on the cushion pins emulates altered process condition, e.g. moving the die from one press to another with a different elastic behavior. In this paper the changing process conditions are just assumed, but if the method should be applied to a real die the influence from the changing process conditions must be known together with the desired pressure distribution.

The scenario of changing process conditions often happens when a real die is moved between a try-out press and the production press, or between two production lines at any time during its lifetime. The optimisation routine is using the forces acting on spacer blocks and cushion pins as design variables. The design variables, consisting of eighteen forces in this study, can be altered in a real die by adjusting shims thicknesses.

A flexible simulation environment using MATLAB as server and ABAQUS as client is used. The ABAQUS FE-model is executed from MATLAB. The results from the FE-model are exported as text files and automatically read back into MATLAB. The function fmincon from the MATLAB Optimization Toolbox is then used for the optimisation in MATLAB. fmincon is trying to minimize a weighted function, $S$ in Eq.(1), depending on the difference between the highest and lowest pressure on the blankholder ($p$), the total force acting on the blankholder surface ($F$), and the number of nodes in contact ($n$). $w_p$, $w_F$ and $w_n$ are the weight factors. While there is no need to constrain the maximum magnitude of the forces, they are not allowed to take negative values since the forces on real cushion pins and blankholder spacers equals zero if they go out of contact. Minimizing the function $S$ in Eq.(1) will result in an even pressure distribution across the entire blankholder.

$$S = w_p \frac{p}{p_0} - w_F \frac{F}{F_0} - w_n \frac{n}{n_0}$$

Eq.(1) is minimized when the number of nodes in contact between the surfaces and the total force on the blankholder surface increases, and when the difference between the highest and the lowest pressure decreases. The optimization routine is using the resulting variables from the initial pressure distribution, exemplified in Fig.5.(a), as references to normalize its variables using $p_0$, $F_0$ and $n_0$. Normalization is used to increase the numerical stability [6]. fmincon is using the interior-point algorithm during the optimization routine. This algorithm is recommended to be used as the primary choice in any problem where fmincon is applied [5]. The algorithm is suitable for many different types of problems, satisfies bounds at all iterations and recovers from NaN or Inf results. The algorithm differentiates all the variables, the forces in the FE-model, with central differencing and takes a step based on the differentiation.
Central differencing is slower but more accurate than forward differencing which is another option. The direction and length of the step is then chosen based on the objective to minimize the function \( S \) in Eq.(1). When the solution has converged the optimization routine stops executing and the final result is presented in MATLAB.

RESULTS AND DISCUSSION

The method for virtual rework of the die surfaces is very fast, accurate and reduces the need for resource consuming manual rework. The method consists of a few iterations that includes solving a single linear FE-model, reading the deformations with a MATLAB script and automatically moving the nodes on the surface of the die to a new position. It should be possible to use it for dies on an industrial scale as well, as long as the deformations are not too large since large node transformations distorts the elements in the FE-model. Distorted elements makes FE-models unsolvable or unreliable, this is not a problem in this study. An approach to eliminate this problem could be to instead use a model that adjusts the actual geometry and meshes it automatically in each iteration of the virtual rework process. If the method should be used to rework the surfaces of dies it is important to represent the deformations of the press in a reliable way as well. A poor representation of the press deformations in the numerical model will yield reworked surfaces that does not give an ideal pressure distribution in the physical die and thereby requiring more resource demanding manual rework.

![FIGURE 5. (a) Initial pressure distribution when the optimization routine starts. (b) Contact pressure distribution in the FE-model with reworked die surfaces.](image)

The optimization routine for reaching the desired pressure distribution performs well when setting the weight factors of Eq.(1) to \( w_r = 45\), \( w_F = 5\), and \( w_p = 50\). It reaches an even pressure distribution and gives the values \( p/p_0 = 0.44\), \( F/F_0 = 0.99\), and \( n/n_0 = 1\). The total time for the optimization is 21 hours, during that time \textit{fmincon} is iterated 75 times and each function call (ABAQUS run) takes 15-20 seconds. The resulting pressure distribution, shown in Fig.5.(b), is very similar to the distribution in Fig.4.(b). Initially the weight factors were equal, however the weight \( w_F \) could be reduced quite a lot without disturbing the result. This is logical in this case since the die was adjusted in the chapter “Virtual rework of the die surfaces” with small forces acting on the blankholder spacers compared to the cushion pins. It is therefore known that the forces acting on them will be small and of low influence when there is an even pressure distribution on the blankholder surface. It is however found that the force term of Eq.(1) cannot be removed completely since some nodes will go out of contact, reducing the area in contact on the blankholder surface. Reducing \( w_F \) also gives the benefit of focusing on \( w_p \) and \( w_r \) which is influencing the results a lot more in this case. These two weight factors have roughly the same values.

A challenge with the suggested optimization approach, applying it up to dies on an industrial scale, will probably be optimization run times. This small model with a very coarse mesh takes between a few hours up to 12 hours to optimize, with 16 cores available for the ABAQUS solver. Therefore, the optimization code and the structural model must be created to run as fast as possible. Reduction techniques for the number of degrees of freedom in the model can help [7] or the method of submodeling [3] in ABAQUS if the analysis is focusing on a small area of the blankholder surfaces.
CONCLUSION AND FURTHER RESEARCH

The suggested and demonstrated methods for virtual rework and optimization of stamping dies are parts of a modern framework simulation-driven design of stamping dies. The method for virtual rework has the potential to drastically reduce the try-out process for stamping dies, as long as it is made with correct representations of process conditions. The optimization routine can be part of a future toolbox of simulation tools intended for simulation support for try-out and running production. Further development of simulation tools like these are important for reduced lead times of new products and competitive production.

FIGURE 6. Framework for a modern simulation-driven design of stamping dies.

The suggested optimization routine shows a high potential to be useful in analyses of stamping dies. In this paper it is demonstrated that the optimization method works. However, additional research is needed. First and foremost the method needs to be applicable to an industrial scale die. This is primarily believed to be a question of being able to reduce optimization run times. Since the structural FE-model is the most time consuming part in the routine it is important to reduce the time for each function call as well as the number of calls. Evaluating other types of optimization algorithms, comparing forward and central differencing, and determining the optimum perturbation steps for the differentiation are suggestions for further reducing the number and length of function calls.

The adjustment of shims thickness must be possible to predict based on set of forces from the optimization. A method is hence needed to go back and forth between shims thickness and calculated force values.

Modeling or measurements of the press line to include its elastic behavior in the FE-model is critical if the presented approach should be possible to use. Modeling of the entire press is often impossible due to a lack of data and CAD-models. Instead measurements can probably be used, but more research into which techniques to use and how to incorporate them into the FE-model is needed.

Coupling of this technique with SMF simulations is the next logical step. The ideal way of doing this is to work with experimental dies. A benefit of working on an experimental die, preferably a small single action die, is that the influence of the deformation of the press line will be minimized. Focus can then be put on the optimization process, the internal deformations of the die, and the adjusting mechanisms of the die. Furthermore, an experimental die is often quite simple with few cushion pins and spacer blocks. They are also often symmetrical which can be used as an advantage in the FE-modeling. This will yield a shorter optimization time since it is directly proportional towards the number of elements and variables in the model.

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5. MATLAB, User manual, Version 2011b, MathWorks
Characterizing the Elastic Behaviour of a Press Table through Topology Optimization

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Abstract. Sheet metal forming in the car industry is a highly competitive area. The use of digital techniques and numerical methods are therefore of high interest for reduced costs and lead times. One method for reducing the try-out phase is virtual rework of die surfaces. The virtual rework is based on Finite Element (FE) simulations and can reduce and support manual rework. The elastic behaviour of dies and presses must be represented in a reliable way in FE-models to be able to perform virtual rework. CAD-models exists for nearly all dies today, but not for press lines. A full geometrical representation of presses will also yield very large FE-models. This paper will discuss and demonstrate a strategy for measuring and characterizing a press table for inclusion in FE-models. The measurements of the elastic press deformations is carried out with force transducers and an ARAMIS 3D optical measurement system. The press table is then inverse modelled by topology optimization using the recorded results as boundary conditions. Finally, the press table is coupled with a FE-model of a die to demonstrate its influence on the deformations. This indicates the importance of having a reliable representation of the press deformations during virtual rework.

1. Introduction

The modern automotive stamping industry is highly competitive and is therefore continuously increasing its usage of numerical simulation software. These software are used to achieve reliable stamping processes, support running production, and for achieving a shorter lead time for stamping dies and car projects.

One numerical method which isn’t used on a wide industrial scale yet is virtual rework of forming surfaces in stamping dies, see Lingbeek [1]. This rework is performed by numerical algorithms and based on Finite Element (FE) simulations of the stamping die and the forming of the sheet. Virtual rework has the potential to support and reduce the expensive and time consuming process of manual rework during the try-out phase of stamping dies. Rework of forming surfaces is done to compensate against elastic deformations of dies and presses, and to reach a desired pressure distribution between the sheet and the forming surfaces.

While performing virtual rework it is often challenging to accurately predict the elastic behavior of the stamping presses. The stamping die is often easier to represent since a reliable CAD-model almost always exists. This paper suggests a method to inverse model the elastic behavior of a press table through topology optimization. The goal of the optimization is to replicate deformations of a loaded
press table recorded with a 3D camera measurement system. The method will yield a press table that is deflecting and deforming. This is another strategy compared to previous work which often includes deflections, and sometimes but not always deformations [2-4]. This strategy will also enable a characterization of the press even when there is no available information about the structure below the table and above the ram(s).

2. Method
A double action press is loaded in three different ways, the deformations of the press are measured with a 3D camera measurement system together with the magnitude of the load. The recorded deformations are then used as constraints in a topology optimization which aim to replicate the elastic behaviour of the press table. This chapter describes the methods in detail.

2.1. Press deformation measurements
The measured press is a Danly double action press at Volvo Cars stamping plant in Olofström, Sweden. The press table is 144x96 inches. The maximum force of the inner slide is 1000 US tons and 600 US tons for the outer slide. The press can be seen in figure 1.

The measurement system is a GOM ARAMIS 5M [5] with 8mm Schneider-lenses and a distance between the cameras of 1220 mm. The frequency of the cameras is set to 15 Hz with a shutter speed of 35.818 ms. The actual ARAMIS system can be seen in figure 2.

A blankholder plate is mounted in the press and the force acting on the press table is applied by the outer ram. The force is transferred between the outer ram and the table through the blankholder plate and four steel pillars. The steel pillars are placed in two different formations which are visualized in figures 3 and 4. Force transducers on each pillar record the forces acting on each pillar. References that are tracked by the ARAMIS system are placed on the ram, the table, the steel pillars, the force transducers and the blankholder plate.

During the measurements the ram is stopped for a few seconds in its lowest position to achieve a stable static measurement of forces and deformations with as little dynamic effects as possible. It is the deformations in this position that is compared with the unloaded press table.
2.2. Inverse modelling of press deformations by topology optimization
The recorded deformations from the ARAMIS measurements are used as constraints when the press table is inverse modelled. The deformation and initial position of each measured point is extracted in the software ARAMIS Professional 2016 and exported as a text file. Since the measurements aren’t covering the entire table the deformations are extrapolated across the entire table with least square fitting and a second order polynomial in MATLAB R2011b [6]. All points are assumed to be positioned on a horizontal plane before the table is deformed. Three measured load cases are selected for the inverse modelling of the table, they are selected so that all the positions of the pillars are included in the simulations. The three load cases are presented in subsection 3.1.

An Optistruct FE-model for topology optimization are created in Hypermesh [7], depicted in figure 5. The red part has the same size as the real press table of the Danly press. Underneath the table there is a blue design volume. The bottom part of the model is locked in all directions. Steel pillars are placed on top of the press table in all measured positions. The numbering of the positions and the forces can also be seen in figure 5.
The goal of the topology optimization is to minimize the volume of the blue design volume. A large reduction will result in very large deformations in the z-direction. Without any constraints on the deformations the volume will be reduced to zero and the deformations of the table will go towards infinity. However, if the measured deformations are used as constraints the volume will be decreased until the deformations match the set constraints. The more measured load cases that are included into the topology optimization the closer the table will mimic the behavior of the real press table. The constraints in the model are set with a tolerance of ±10 percent of the total measured deformation in each point due to noise and vibrations in the measured values. Otherwise it will be hard for the optimization routine to find a feasible solution. In future work the tolerance should be based on estimations of noise, error and dynamic effects in the ARAMIS measurement.

2.3. Structural analysis of a stamping die
A structural model of a matrix from a stamping die is solved in Optistruct, when it is loaded with a blankholder pressure extracted from a sheet metal forming (SMF) simulation. The die is placed both on a rigid surface and the optimized press table. This will visualize the influence of the press deformation on a stamping die and also give an indication of how much virtual rework of the die surfaces that are needed. The aim of virtual rework is normally that the die surfaces shall move into their nominal position from the original construction when the die is loaded [8].

3. Results
This chapter describes the results from the press measurements, the inverse modelling of the press table by topology optimization, and the structural simulation of a stamping die.

3.1. Press measurements
An example of measured deformations visualized with vectors in ARAMIS Professional 2016 is depicted in figure 6. As can be seen there are not points covering the entire press table. This is one of the reasons for why the deformations were extrapolated across the entire table. Another reason is that the least square fitting is smoothing the deformations, this is desired since there will always be some noise in measured data.

The measured forces from the three load cases (LC), LC1-LC3, selected for the topology optimization is presented in table 1. The deformations in z-direction extrapolated across the entire table based on the ARAMIS measurements can be seen in figure 8, 10 and 12.

![Figure 6. Deformations represented with vectors in ARAMIS](image-url)
Table 1. Applied loads in LC1-LC3 (metric tonnes)

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<td>-</td>
<td>42.98</td>
<td>-</td>
</tr>
<tr>
<td>LC2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>77.62</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>82.99</td>
</tr>
<tr>
<td>LC3</td>
<td>-</td>
<td>75.76</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>75.38</td>
<td>-</td>
</tr>
</tbody>
</table>

3.2. Inverse modelling of press deformations by topology optimization

The optimized design volume is depicted in figure 7, the solids in the figure is shown with some transparency for a better visualization of the final geometry. When the optimized model is loaded with the forces in LC1-LC3 the resulting deformation in z-direction are seen in figure 9, 10, and 11.
3.3. Structural analysis of a stamping die
The deformations in z-direction for the matrix on a rigid press table is visualized in figure 14, if the matrix is placed on the inverse modelled table the deformations will increase to what is seen in figure 15. If the deformations in figure 15 are magnified it can clearly be seen that the matrix is both deflecting and deforming in many different ways, see figure 16. A comparison of the die surfaces in a best fit position can be seen in figure 17.

Figure 14. Deformation on rigid press table. Note that the colour range is different from figure 16.

Figure 15. Deformation on topology optimized press table. Note that the colour range is different from figure 15.

Figure 16. Magnified deformations for the matrix on the topology optimized press table.
4. Discussion & Conclusion

The suggested method for inverse modelling of a press table through topology optimization is accurate for the three presented load cases. A good approximation of the die deformations should therefore be reached when a blankholder pressure from a SMF simulation is applied to a matrix positioned on the table. A major benefit of this method is that both deflection and deformations are included and inverse modelled in a single topology optimization step.

However, for a full characterization of the press table more load positions should be included. Since the steel pillars were placed around the edges of the table in these measurements it is uncertain if the deformations will be reliable when the punch is applying pressure to the middle of the matrix and the table. A good idea would probably be to use the load positions in this paper together with the suggested positions in [3] for an even better estimation of the entire table. The inverse modeling will never yield a better result than what is fed into the topology optimization, more and better data will give a more accurate final result.

To be able to accurately rework the die in a virtual try-out environment the inner and outer ram needs to be inverse modelled as well. It is only when the entire system with all the die and press parts are loaded together that the calculated deformations will resemble the deformations of the real die.

One potential problem is also that the measurement did not cover the entire press table. This gives uncertainties about the deformations outside the actual measured area. The distance between the cameras can be increased which will enable the system to measure a larger area. However, for larger press tables it will probably not be sufficient with one ARAMIS system measuring from one position. Several measurements will have to be made in different positions. The measurements will then have to be stitched together, or the number of load cases in the topology optimization needs to be increased.

Another problem in a stamping plant that this method can support and visualize is that the same stamping die can produce different geometrical output in different press lines. One factor, probably major, influencing this is the elastic behavior of the press itself. This can be visualized and analyzed through the methods presented in this paper.

5. Future Work

The next step in this research will be to characterize the outer ram of the press as well. When that step is completed it will be possible to perform a virtual rework of the forming surfaces of the blankholder and the matrix.
To be able to virtually rework the punch, additional measurements and optimizations with loads on the inner ram, and simulations with the punch, will be needed. An investigation into which deformations the virtual rework should compensate for is also needed, the larger deformations in figure 16 or something more similar to the smaller deformations in figure 17.

An assumption made in this research was that all the points on the press table are initially situated on a horizontal plane. A method to include the real initial geometry and position of the upper surface of the table should be applied in future work. Otherwise it is a potential error source that can influence the virtual rework.

A method to verify the calculated deformations of the stamping die is also needed. This can be achieved by placing references on the outer parts of the die itself and filming it with an ARAMIS system [9]. These deformations should match the simulated ones.

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