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Macro-Geometric Defects

- A numerical and experimental study of springback and surface defects

LUND UNIVERSITY

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Abstract

Today, shortened lead-times in the automotive industry have dramatically increased the need for more efficient development methods at every stage of the process development chain. In order to decrease the long lead-time for producing a forming tool, sheet-metal-forming simulation was introduced. Even though sheet-metal-forming simulation is widely used in the automotive industry today, there are still challenges to be overcome. Two important examples are the prediction of springback and surface defects. If reliable predictions of these phenomena could be achieved, much money could be saved in reduced lead-times and adjustment costs.

This thesis consists of seven papers in which the above-mentioned phenomena have been analysed, both experimentally and numerically. This has, among other things, resulted in a methodology for analysing surface defects both numerically and experimentally using the same evaluation software and criteria. The work also includes analyses of the control of the material flow by optimising the restraining force of the drawbeads. Furthermore, a method with which to efficiently identify "gaps" (which is a search fo possible deficiencies in the process) in conjunction with the process analysis has been introduced, together with a proposal for efficient information handling.

The Production Performance Matrix (PSM) can be used to determine which parameters have a significant effect on a process. The PSM is a structured way to extract significant parameters in a process in order to find where the most output for the least input will be achieved in order to improve the process. The PSM was further developed into a Process Correspondence Matrix (PCM), in which two different processes, FE simulation versus try-out tools, were analysed and compared. It was found that the study of drawbeads, springback and surface defects was of significant interest.

To successfully implement sheet-metal-forming simulation it is important to establish an efficient exchange of information. Efficient information handling will also generate a more accurate basis for decisions aimed at reducing the number of changes in the development phase of producing a specific automotive part or evolving a certain process. Efficient information exchange can be established by using a database in which animations from the sheet-metal-forming simulations are stored. The database should be accessible from the Internet in order to enable direct investigation and analysis by authorised persons.

In the forming process the flow of material is controlled among other things by drawbeads. The material flow is very important in order to have a correct stress distribution in the formed part, which in turn affects both springback and surface

defects. Therefore it is important to provide a good description of the drawbeads. In FE simulation the drawbeads are described by a restraining force. In this work a method for optimising the restraining force with a small number of iterations has been developed. The results indicated good agreement with the physical drawbead geometry for the analysed tool.

Regarding springback, a study of the parameters resulted in the conclusion that the important factors to consider in FE simulations of springback are, among others, to have small elements, low tool speed and good material models. The results were applied to an automotive part, a front side member. The simulations exaggerated the twist but the error was moderate for mild steel and Rephos steel. However, a TRIP steel was also examined and there the deviation was much larger. Furthermore, the TRIP steel showed much larger springback than the other materials and therefore this must be taken into consideration when TRIP steel is used for automotive applications.

Analysis of surface defects involves difficulties in both experimental and numerical assessment. Since the defects are very small and also depend on both position and shape in the classification procedure, it is difficult to find an evaluation system which can detect both small variance in the shape of the surface and classify the defects. Furthermore, the numerical results depend both on the accuracy in the prediction of the forming behaviour and the springback. In order to compare the results of the same classification procedure, a method has been developed whereby the surface can be analysed both numerically and experimentally in the same evaluation software. In this way, the classification will be the same and the results will be directly comparable. The method has been used on both an experimental panel and an automotive panel (outer panel of a door). For verification, these results were also compared both to manual inspection and evaluation in commercial evaluation tools.

Key words: Sheet-metal forming, Simulation, Finite element analysis, Information exchange, Springback, Surface defects, Drawbead, Optimisation, Process analyse
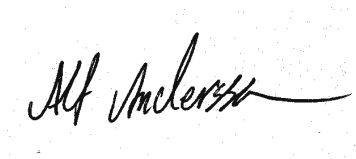
Preface

This thesis analyses the potential of sheet-metal-forming simulation. Special emphasis is placed on this potential in predicting springback and surface defects, and its ability to analyse surface defects with the same evaluation criteria experimentally and numerically. The work for this thesis has mainly been carried out at the Department of Virtual Verification at Volvo Cars, Body Components (VCBC) in Olofström, Sweden, and is a joint effort between VCBC and the Division of Production and Materials Engineering at Lund University. It has also been financially supported by PROPER and ProViking. In a previous work [1] papers A-C were treated. This thesis is based on that work together with extended studies within the area and comprises the following papers:

A   A. Andersson, Comparison of sheet-metal-forming simulation and try-out tools in the design of a forming tool, Journal of Engineering Design 15 (3) (2004).

B   A. Andersson, Information Exchange within the area of tool design and sheet-metal-forming simulations, Journal of Engineering Design 12 (4) (2001) 283-291.

C   A. Andersson and J. Hertzman, Evaluation and comparison of surface defects on a simplified model for the area around the fuel filler lid by simulation and experiments, NUMIFORM 2001, Toyohashi, Japan, 2001.

D   A. Andersson and S. Holmberg, Simulation and verification of different parameters effect on springback results, NUMISHEET 2002, Jeju Island, Korea, 2002.

E   T. Jansson, A. Andersson and L. Nilsson, Optimisation of Draw-In for an Automotive Sheet Metal Part, Submitted for publication in Journal of Materials Processing Technology.

F   A. Andersson, Numerical and experimental evaluation of springback in a front side member, Submitted for publication in Journal of Materials Processing Technology.

G   A. Andersson, Evaluation and visualisation of surface defects on automotive panels, Submitted for publication in Journal of Materials Processing Technology.

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My supervisor at VCBC was Peter Arvidsson (now at Tetra Pak) and Professor Claes Magnusson, whom I owe many thanks for the inspiring and fruitful discussions during my work.

Many thanks to my friends at the Department of Virtual Verification at VCBC for the creative atmosphere and keen discussions. I would also like to thank my colleagues at VCBC who helped me with experiments and advice during the work with this thesis.

I am also very grateful to my colleagues at IDC in Olofström (Industrial Development Centre in Olofström) for highly productive discussions and for all their help with the experiments. Especially I would like to thank, Fredrik Krantz (now at ProEngCo) and Jörgen Hertzman (co-author of Paper C) for their support. I would also like to thank all my friends, especially Anna Runnemalm, for their help with comments and suggestions during my work.

This work has mainly been carried out at Volvo Cars Body Components (VCBC) in Olofström, Sweden, and is a joint effort between VCBC and the Department of Production and Materials Engineering at Lund University. I have also been a part of the PostGraduate Programme at Volvo which has been a great opportunity to share research within Volvo and has contributed encouraging discussions over many different research fields. The work has been financially supported by PROPER and ProViking, which is gratefully acknowledged.

Finally, but not least, I would like to thank my family and my greatest source of encouragement during this work, namely my wife Pernilla and my daughter Klara. They have always believed in me and encouraged me in my work and have given me perspective to see the importance of a life beside the research.

Contents

Appended papers:

Paper A: Comparison of sheet-metal-forming simulation and try-out tools in the design of a forming tool

Paper B: Information exchange within the area of tool design and sheet-metal-forming simulations

Paper C: Evaluation and comparison of surface defects on a simplified model for the area around the fuel filler lid by simulation and experiments

Paper D: Simulation and verification of different parameters effect on springback results

Paper E: Optimisation of draw-in for an automotive sheet metal part – An evaluation using surrogate models and response surfaces

Paper F: Numerical and experimental evaluation of springback in a front side member

Paper G: Evaluation and visualisation of surface defects on auto-body panels

1 Introduction

Today, lead-times in the automotive industry must be as short as possible. Short lead-times have dramatically increased the need for more efficient development work at each stage of the process development chain. FE simulations of the sheet-metal-forming process can be used for this purpose. Sheet-metal-forming simulation has become more common in the automotive industry over the past decade and is an efficient technique for many applications. Its most significant advantages compared with try-out tools are the substantial reductions in time and cost. The use of sheet-metal-forming simulation in the automotive industry has been described by Makinouchi [2] and Makinouchi et al. [3].

This thesis analyses the potential of sheet-metal-forming simulation. Special focus has been on the potential of sheet-metal-forming simulation for predicting springback and surface defects, which are examples of macro-geometric defects. Many studies have been done within the area covered by this thesis, but only a selection has been referred to.

The interaction between the tool design process and sheet-metal-forming simulation is described in Figure 1.
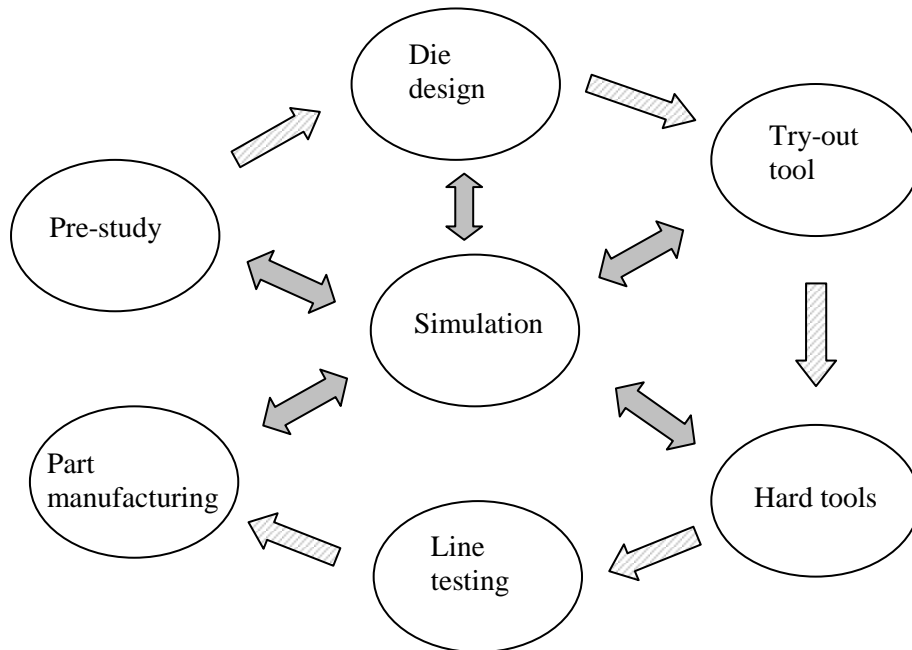
Figure 1: Interaction between tool design process and sheet-metal forming simulation.

Today it is possible to predict thinning, cracks and tool forces with high accuracy, but still remain important challenges.

One such challenge is the prediction of surface defects. Surface defects are small deviations from the nominal surface of an automotive part. These defects can be of varying sizes and depths. Defects with relatively large depths (wrinkles) are visible in an optical check, while small defects are detected manually by a specialist making a tactile examination of the part, or by optical inspection in a light-frame. Small defects do not become visible until the part has been painted, which means that the painted part must be adjusted/repainted or scrapped, giving rise to unnecessary costs and losses in productivity. Today, there are methods to detect small defects by using non-contact measurements [4-7]. These methods are able to visualise the defects but are limited in efficiency and repeatability. Another disadvantage is that the interpretation of results is not correlated to the subjective scale, which is used at Volvo today. Thus it is very difficult to define the limits between accepted and not accepted defects. In figure 2 an example of surface defects is shown. The surface is analysed with the WMS [8]/NXT post processor [9] (see paper G) where the blue areas indicate depressions.

Figure 2: Example of visualisation of surface defects.

Hartung [10] carried out studies in which he compared finite element (FE) simulations and measured surfaces with good agreement regarding the appearance of defects, but did not compare the results on the same scale.

Another challenge is the prediction of springback. Springback is a phenomenon that can be described as a change in geometry occurring after the parts have been removed from the forming tool. This geometry change can cause mismatch between the part and others when they are assembled. In order to obtain the correct geometry after forming, compensation is added in the design of the forming tools. The amount of compensation is based on educated guesses that are based on experience. However, it is difficult to make an accurate prediction by educated guesses which lead to much time and money being spent on trial and error. This trial and error procedure could be minimised by using sheet-metal-forming simulation in the tool design process.

Another important issue to be addressed in order to decrease the lead-time is to achieve more rapid and more accurate information exchange. Information exchange has always been vital for the success of complex projects such as producing a forming tool. In the past decade information exchange has changed both in terms of methods and channels. Information methods can be defined as ways of achieving accurate information, and information channels can be defined as the ways the information is distributed. The increased pressure to shorten lead-time has accelerated demands on better and faster information exchange. In figure 3 an example of the information exchange for a tool manufacturing process is shown.
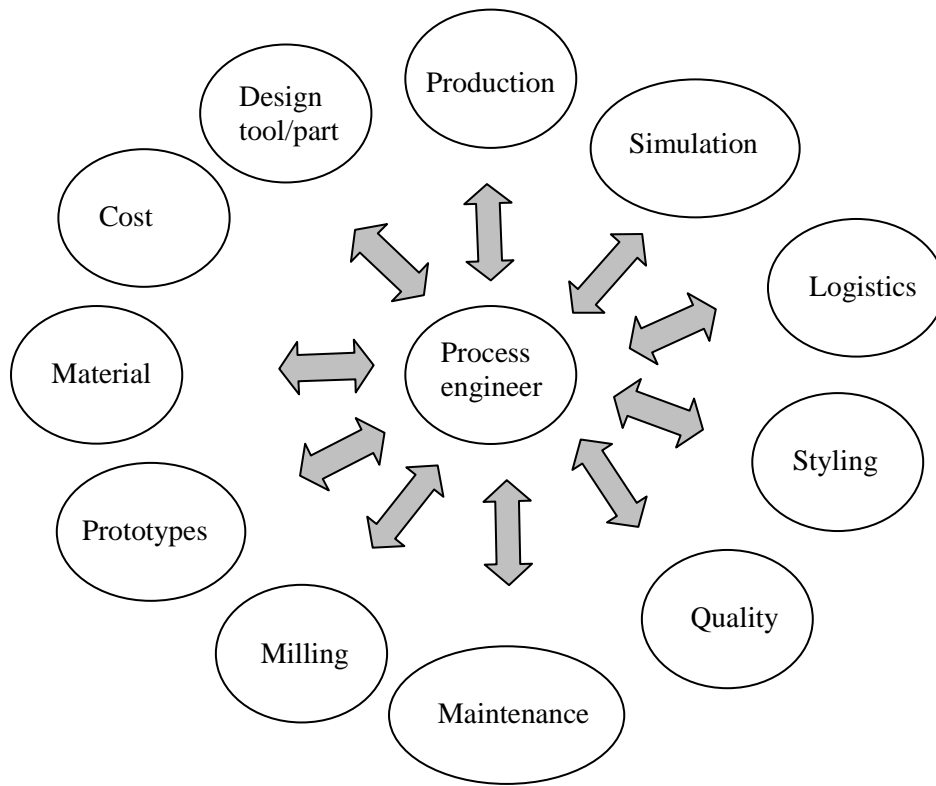
Figure 3: Information exchange in a tool manufacturing process.

2 Research position and problem formulation

Research work can be divided into different areas depending on the aim of the research. In figure 4 the hierarchy is described as a pyramid where the added value increases the higher up in the pyramid one comes. For comparison, the funding of Swedish research can also be found in figure 4. It can be seen that the main part of the research is done in the area of industrial research.

Research areas   **Proportion of funding of Swedish research**

Source: http://www.vinnova.se, FoU i Sverige 1999.
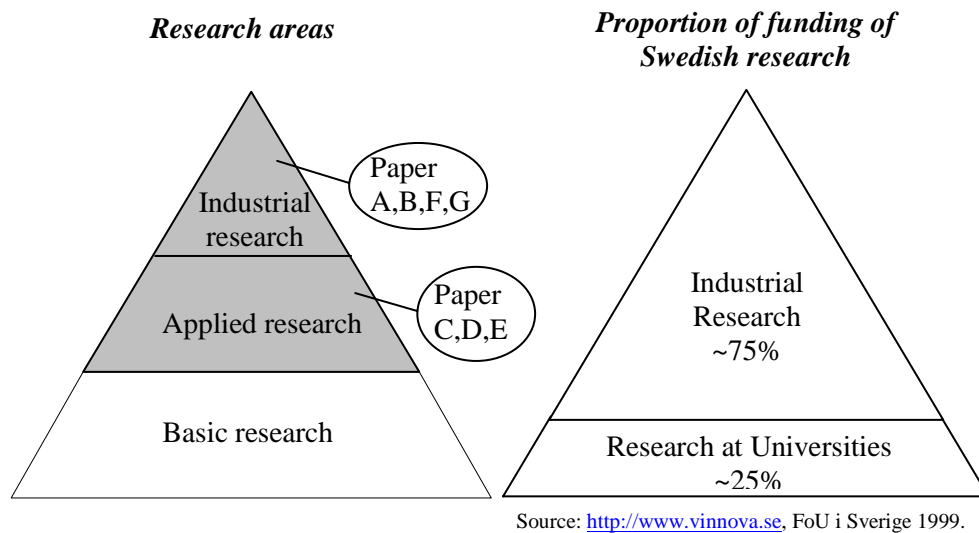
Figure 4: Definition of research areas and funding structure of research projects.

In figure 4 the following areas are described:

- Basic research: Research which is the foundation within an area. This is done mainly by universities.
- Applied research: Implementation of basic research on the laboratory scale for the evaluation of processes by tests, which are easy to control and perform parameter tests in.
- Industrial research: Application of the techniques developed in the laboratory tests in industrial cases.

This thesis is positioned from the middle to the top of the pyramid and stretches over two areas (marked with grey in figure 4). The motivation is that known applications were applied in laboratory examples. These tests were evaluated and implemented in industrial applications for verification and validation of their usefulness on the industrial scale. The use of sheet-metal-forming simulation have been discussed in paper A, where the areas of drawbeads, springback and surface

defects were defined as areas with high improvement potential in the field of sheet-metal-forming simulations. These are connected by the fact that the drawbeads, among other parameters, control the material flow. The material flow affects the springback, which again affects the surface defects (figure 5).

Figure 5: Connection between the subjects analysed in the thesis.

Relevant research is described in section 3. This section focuses mainly on macro-geometric defects since this is the most important issue to be solved.

The desired material flow can be achieved by manual adjustments of the process and the drawbeads fairly easily in the try-out process. This is done by analysing and comparing the draw-in by the simulation and given by the experiments. It is much more cost-effective to adjust the drawbeads or the process than to remill the shape of the tool in order to compensate for springback.

2.1   Research question

The research question can be formulated as follows:

How can FE simulation be used to improve the manufacturing process, in particular addressed to macro-geometric defects?

In academia the answer to the research question reveals weaknesses in the existing numerical tools and therefore the research can be addressed to relevant issues in order to improve the accuracy of the prediction of the process design.

3   Methodology

The research need is defined in paper A. Here the state-of-the-art of forming simulation is analysed and a deficiency in the simulation technique is defined within the area of springback, surface defects and drawbeads. Therefore, these areas are analysed, with a focus on springback and surface defects. Drawbeads generate an important input to the results for springback and surface defects, since the material flow is normally controlled by drawbeads in the automotive industry. Therefore it is important to have control over the effect of drawbeads in the simulation of sheet-metal forming. Furthermore, a proposal for a reporting strategy was treated, since it is important to be able to communicate the results to

all concerned. This avoids leaks in the information chain and big costs can be saved by doing the correct thing from the start. Efficient information exchange also decreases the lead-time.

A methodology for computational support in product development and its application to a production process is described in [11, 12]. This can be adapted to a process-based approach like the one used in these studies.

Regarding the technical aspect of the research, the following methodology was used. In laboratory test examples different techniques were tested and simulation results were assessed and compared with experimental results. These results were then implemented in industrial applications. The advantage of this method is that many parameter settings can be assessed and the best choice of parameters can be used for further testing in an industrial application. Furthermore, the models are well defined and can easily be modelled. This minimises the uncertainty of how much the inaccuracy in the modelling affects the results, and certain effects can be isolated and evaluated.

The methodology is described in figure 6.
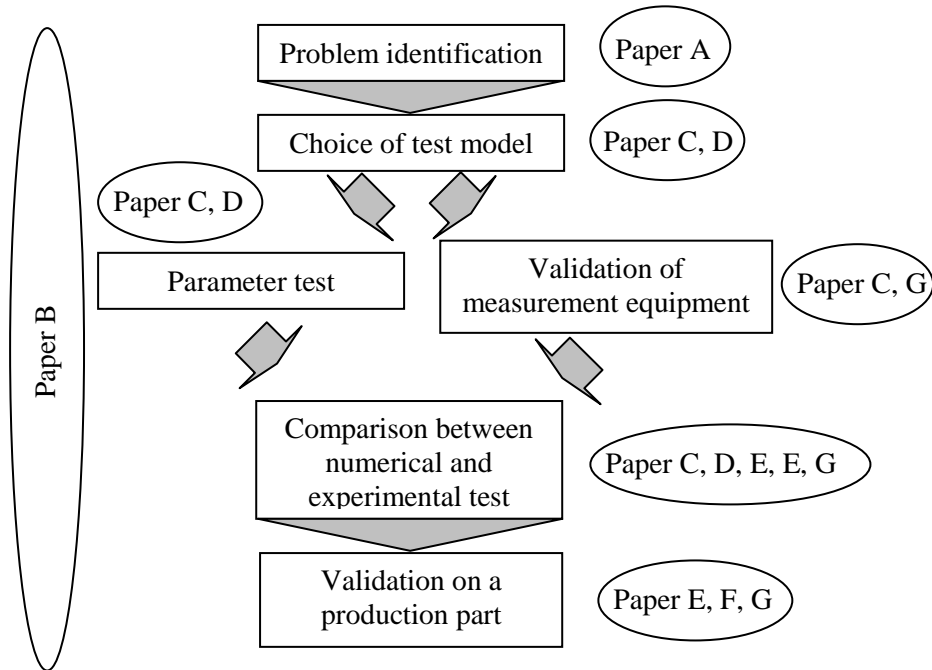
Figure 6: *Methodology of research work and the relation to the appended papers.*

4 Sheet-metal-forming development

Sheet-metal-forming simulation is nowadays relatively common in the automotive industry and is an efficient technique in many applications. At the Volvo Cars Body Components (VCBC) this was initiated in the early 90's, [13-15]. The most significant advantages compared with try-out tools are the substantial reductions in time (by a factor 15) and cost (by a factor 10). For each try-out tool, furthermore, it is important to have an efficient strategy for analysing the significant factors which affect the process. This can be done by using the Production Performance Matrix (PSM) [16] and the Production Comparison Matrix (PCM). This is described in paper A.

For all organisations, it is important to have an efficient technology transfer from R&D to the process. Pantano [17] studied this at the FORD Motor Company and found that the big variety of cultures, organisations and company structures there create big challenges for the creation of an efficient transfer of technology. He concluded that it is of vital importance that the transfer of technological information is shared by the researcher and other organisational entities. Applying this to the sheet-metal-forming process it can be concluded that it is important for the efficient use of the simulation results. These results must be accessible to the rest of the organisation and their interpretation must be readable and understandable so that all affected personnel can interpret the results correctly. The easier the access to the results, the more time and expense will be saved, since the decisions made will be faster and more correct. One method to achieve this is proposed in paper B. There are many proposals for the solution for efficient result-databases, e.g. Cardew-Hall et al. [18], but the advantage of the method proposed in paper B is that the user can analyse the forming process and its consequences directly. The only requirement is that there is a connection to the database where the results are stored. This connection can be, for instance, the Internet.

5 Drawbeads

The material flow is controlled by drawbeads in most forming processes. The drawbeads apply a restraining force to the blank and the size and shape decides how much the material will move during the forming process. In figure 7 a sketch of drawbeads is shown. In paper E an optimisation process of the drawbeads has been analysed. By this method, it is possible to predict suitable drawbead geometry with given constraints for achieving a working process. Studies have been published, e.g. Samuel [19], Shuhui et al. [20] and Mattiasson and Larsson [21], in which a 2D-model of the drawbeads has been used to calculate the drawbead geometry based on a restraining force. However, in this way it is not possible to take all the necessary constraints for a forming process into account.

Another approach is to do analytical studies of the drawbead geometry, Courvoisier [22].

Chen and Weinmann [23], have studied how the drawbead geometry influences the sheet deformation during forming and found that the end geometry of the drawbead has an influence on the sheet deformation. They recommend to have the end radius twice the size of its cross sectional radius.

With the proposed method in paper E, it will also be easy to compare simulation results with experimental results, since the only parameter to be compared is the draw-in. This is easy to measure and gives a process by which the drawbeads are easy to adapt.
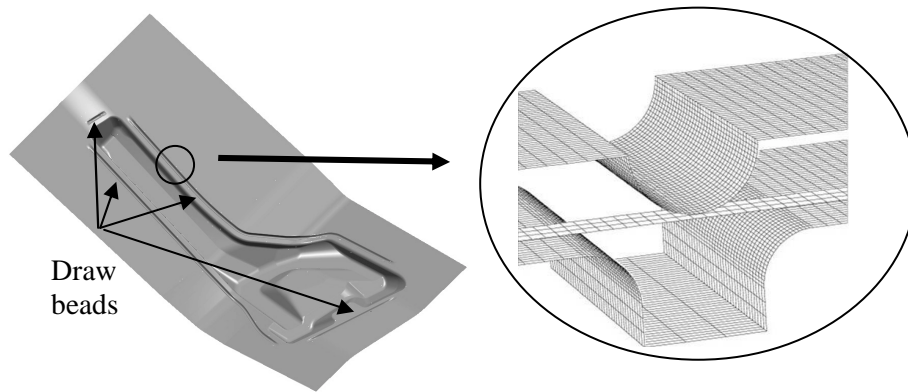
Figure 7: Example of drawbeads. In the picture on the left the drawbeads in a tool are shown and in the picture on the right a simplified model, used for verification of FE simulation results, is shown.

6 Simulation and assessment of macro-geometric defects

Macro-geometric defects can be defined as defects which appear during the forming of thin metal sheets. This work is limited to springback and surface defects. Surface defects are small deviations from the nominal surface of a panel, and can be of varying sizes and depths. The defects can appear as:

- Depressions.
- Elevations.
- Bimps.
- Orange peel-like.
- Local thinning.

Defects with relatively large depths (wrinkles) are visible by an optical check, while small defects are detected by a method in which a specialist manually examines the panel in a light frame or by feeling the surface with his hand. These defects do not become visible for a non-specialist until the panel has been painted. After painting, these defects give an impression of bad quality, since they are perceived as defects in the panel. However, they must be distinguished from the type of defects which appear on the micro scale, i.e. depth variations in the μm-range, e.g. the Ra-value which represents the surface roughness.

Surface defects often appear on relatively flat panels with some kind of embossment, e.g. on doors in the area of the door handle, and on rear fenders with the fuel filler lid. The areas around the corners of the embossments will be subjected to compressive stresses. Since the panels usually have relatively low stiffness in these areas, and the plastic strains are insignificant, they are very sensitive for springback, which results in surface defects.

Springback behaviour depends on many different parameters. Shi and Zhang [24] defined four different types of springback often seen in formed parts.

- Flange/wall angle change.
- Sidewall curl.
- Twist.
- Surface distortion resembling "loose metal" or "surface lows".

The amount of springback in the formed part depends on the stress-field created by the forming operation. When a part is formed, plastic deformations takes place, which in turn causes a residual stress-field in the part after forming. When the part is released from the tool, the stress-field causes a change in the geometry of the part due to relaxation of the above-mentioned stresses. Asnafi [25], in his analytical studies of springback in a double-curved panel found, among others, that tension during forming decreased the springback.

This type of defects cost the automotive industry large amounts of money for the extra operations needed to adjust the defects in order that the surface can be approved. If these operations could be minimised, the potential savings can be counted in millions of dollars per year.

Studies of how the springback can be decreased have been done, see for instance [26, 27]. In these studies, suitable geometry and process conditions were proposed to decrease the springback. Furthermore, an internal Ford research study by Ford Forschungszentrum Aachen [28] has shown that an increased restraining of the blank in the end of the drawing process decrease the springback. An other way to reduce the springback is to control the tool temperature. This was analysed by Moon et al. [29], who found that a reduction of up to 20% of the springback was achieved by the combination hot die and cold punch. Another study by Klamecki

[30] proposed the use of magnetic pulses to reduce residual stress. He showed that a reduction of up to 13% of the residual stresses can be attained for high stress specimens. However, the minimisation of springback was not considered in this study.

6.1 Experimental validation of springback

The validation of the geometric shape is done in the prematching equipment. This is based on pre-defined reference points which are chosen in order to give the most stable results when the prematching is done. The part is placed in the fixture and the geometric deviation is measured. If the deviation is greater than given tolerances, the part is regarded as defect. Of course, the geometry must also be within the required tolerances for the assembled parts after the assembly process. An alternative method, which is not so common, is to apply a defined maximum pressure at the location where the deviation occurred. If the deviation is still outside the tolerances, the part is regarded as defect. The pressure corresponds to the pressure which the welding gun can apply in the assembly process. If this method is used it is important that the measured part does not affect the surrounding parts, to which the measured part is assembled to, so that the assembled body falls outside the tolerances.

These methods give rise to different philosophies regarding the choice of reference points. From the forming point of view, a more preferable strategy would be to choose the reference points on a stable surface e.g. the bottom plane in the case of a U-shape. However, the assembly engineers prefers to choose the reference points on matching surfaces e.g. on the flanges.

Today, the procedure at VCBC to measure the geometry is to use a CMM machine, measure important points and refer them to a CAD model, which represents the perfect geometry. The points are then reported with their relative position with Inside/Outside/Upper/Lower/Front/Back with an index (I/O/U/L/F/B) and a value of the deviation. These values are stored in a database for analysis.

Systems, which can scan the part of the geometry and directly relate the results to the CAD model or to the assembled position, are available on the market e.g. FARO [31]. These systems are either mobile or placed on a fixed base.

Today, softwares which are able to visualise the effect of given reference points and tolerances for every part on the whole car body have been developed. With this software it is possible to see the global result of a set of reference points and their tolerances. An example of such software is RD&T [32]. Another study on the prediction of the assembly error is presented by Koganti [33].

6.2 Sheet-metal-forming simulation of springback

6.2.1 Simulation of springback

Sheet-metal-forming simulation can today predict the forming behaviour of a part with good accuracy. Simulation allows, among other things, an examination of the stress-field in the part. In the springback calculation the stresses that occur in the simulation of the forming process are released. The material model must of course be able to handle the plastic region during the forming process, since the forming operation contains a history of the plastic region.

Several authors, [24, 34-41, 43, 44], have analysed which parameters are most important for the accuracy of the springback simulation and how these should be chosen in order to predict the amount of springback. Most of these studies have treated small experimental parts and have not compared the stress field produced experimentally with the simulated field. However, techniques for measuring a stress field are available which have been described by Walker [45], Xia et al. [46, 47] and Hartung [10].

In order to analyse the significance of different parameters, statistical studies can be used. With this technique it is possible to see how different parameters interact and thus decide their significance. Inamdar et al. [48] did such a study and found that statistical methods can be used for the examination and validation of parameters. Among others, the die gap is important for the springback. More examples are given in section 6.2.2.

In recent time, studies of automotive parts have been published [49-54]. It has been shown that the accuracy in springback prediction for automotive panels have increased e.g. the accuracy is high enough to try die compensation based on simulation results. However, improvements are still necessary.

6.2.2 Important parameters that affect the simulation of springback

The following parameters are very important for the results of the springback simulation.

- Forming velocity, such as the punch velocity and the closing velocity of the blank holder in a dynamic explicit code.
- Die gap.
- Element size.
- Material model.
- Hardening law.
- Material properties.

These parameters will be treated in more detail below.

Another important parameter is the number of integration points. In the literature the recommended setting has been as high as 51 points through the thickness [34]. However, in paper D was 5 integration points through the thickness found to be sufficient.

Forming velocity

A problem in dynamic explicit software is the dynamic effects generated by the punch velocity. In several studies of these effects, e.g. Mattiasson et al. [35] and Hu [36], it was found that springback simulations require lower velocities than ordinary forming simulations in order to generate stable stress. Generally, a value between 1-4 m/s is used according to the literature. This of course depends on the problem. If the speed is too high, the stresses will oscillate during the forming operation and also cause stress relaxation [35]. A large oscillation in stresses affects the springback since the final state in the forming simulation determines the level of the stress-state. A large oscillation means that a minor variation in time leads to a major variation in stress. This was examined in paper E where it was found that an area consisting of several elements must be regarded in the stress analyses. It is not enough to analyse single elements because the surrounding elements can balance the oscillations of the analysed element. Furthermore, a suitable velocity was found to be 2 m/s.

Die gap

Hu [37] did a study which confirmed that the die gap influenced the results. However, the conclusion was that the die gap influences the springback but for any general recommendations further studies were needed. This parameter has not uniquely been a part of this study, but the value of the die gap commonly used is sheet thickness plus 10%.

Element size

The size of the element has a major influence on the simulation results. In order to achieve small and fast simulation models, the element size should be chosen to be as large as possible without loss of accuracy. Since the tools and the blank are normally represented by meshed surfaces it is more convenient to study them separately.

Blank:
Mattiasson et al. [55] found that an element size of half the draw radius is suitable for a forming simulation to give a reasonable strain prediction. In the literature there are indications that a springback calculation requires even smaller elements. Mattiasson et al. [35] found that an element size of 0.1 times the draw radius should be chosen to avoid stress relaxation. Other studies, e.g. Lee and Yang [38], found that the element size should be 0.2 times the draw radius. Since the conclusions vary, it seems reasonable to use an element size as small as possible, but 0.2 times the draw radius would be a good start value. This was also found in the parameter study presented in paper D.

Tools :

There are two different ways to describe the tool surface. The best description is to use the CAD surface as the tool surface. The other is to use meshed surfaces, which is the method most widely used since it is not so sensitive to surface quality. The element size decides how well the surface is represented. The best results are the simulation obtained when the CAD surface is used in the calculation. However, if the surface must be meshed, Lee and Yang [38] found that a suitable relationship between element size and draw radius is 0.15. In paper C VDA-surfaces were used as tool description, but this demands a very simple and perfect surface description. For a production part it is more relevant to use mesh. This was examined in paper E but no convergence could be established for the tool discretisation. However, it is often most important to have a fine mesh in a radius since the material is to change its flow direction in its passage. In this case a suitable element size corresponds to a chorda deviation of a maximum of 0.1 mm and at least 9-12 elements over the radius.

Material models

In order to describe the deformation behaviour of a material, different material models are used. Since springback depends on the stress field generated in the forming process, it is very important to obtain accurate results in the sheet-metal-forming simulation. This means that the better the description of the forming process, the better the accuracy of the springback simulation. Geng and Wagoner [39] concluded that the model by Barlat et al. (Barlat'96) [56] gave best results for a 6022-T4 aluminium alloy in a strip draw-bend test, described by Carden et al. [40], in comparison with the model by Barlat and Lian (Barlat'89) [57], the model by Hill (Hill'48) [58] and the model by Von Mises [59]. In paper G Hill'48 and Barlat'89 material models were compared and it was concluded that Barlat'89 model generated more accurate results than Hill'48. Furthermore, Karafillis and Boyce [60] presented a new material model 1993. Andersson et al. [61] found that this model provided even better agreement with experimental values in the forming simulation than the Barlat'89 or the Hill'48 material model. This indicates a potential for better accuracy also in springback simulations.

Hardening laws and material properties

The forming of a part normally involves both bending and unbending of the material. When the material is formed, the yield surface will change in size and position. The bending and unbending causes an effect called the Bauschinger effect, see [62, 63]. In order to describe this numerically, different hardening laws are used, e.g. kinematic hardening or mixed hardening. Another common way to describe the hardening is to use isotropic hardening in which case the Bauschinger effect is neglected. In the literature, many authors have studied these phenomena. For example, Mattiasson et al. [35] found that kinematic hardening corresponded better to the experiments than isotropic hardening. Chu [41] however, found that mixed hardening agrees better with experimental results than kinematic and isotropic hardening. Furthermore, experimental evaluation and implementation into numerical simulations has been investigated by Zhao and

Lee [42] and in the IMS project 3DS- Digital Die Design System (contract G1RD-CT-2000-00104) [43].

In paper G the results of the 3DS-project have been tested and evaluated. It was found that the hardening model has an effect on the results, and mixed hardening gives higher accuracy than isotropic hardening.

Shi and Zhang [24] compared different hardening behaviours and found that the r- and n-values, which describe the anisotropy and the hardening of the material, respectively, have a big influence on the results. They found that the peak n-value influences the springback results. Therefore, it is important to use actual stress-strain data instead of data calculated from n- and K-values. Hu [36] found that it is desirable to use different r-values in the rolling direction and transverse direction in order to calculate springback. Hu also found that the springback is sensitive to the friction coefficient. Young's modulus is very important for the springback. Studies have been done in this area, Li et al. [44], and the results indicate that Young's modulus does change during the forming. However, the magnitude is usually small and it is probably not a significant parameter for the springback simulation.

6.2.3 Springback simulation

The goal of the simulation is to predict the springback for production parts. There are examples of comparisons between simulations and experimental results for automotive parts in the literature [49-54, 64, 65]. It can be concluded that the choice of material model and element size greatly influence on the results. Furthermore, the studies showed that the accuracy of the springback prediction has increased due to the knowledge gained during the last years, and is now high enough to compensate the tool with respect to springback. However, the accuracy can still be improved. An example of this are the results reported in paper F where the predicted springback was overestimated and, especially for TRIP steel, the result needs to be improved to be reliable. Low accuracy regarding TRIP steel has also been found in a study by Pehrsson and Liljengren [66].

6.2.4 Conclusion

Springback simulation requires smaller elements than does an ordinary forming simulation. A suitable element size for the blank is 20% of the draw radius. Larger elements cause relaxation of stresses.

In dynamic explicit codes, a suitable tool speed is lower in springback simulation than in ordinary forming simulation since excessive speed causes unstable stress-distribution and stress relaxation. From the literature it can be concluded that a suitable tool speed is 1-4 m/s. Obviously the binder wrap and the forming must be separated and the speed is also dependent on the amount of curvature and the amount of "free" material during the forming process.

The material properties have a great influence on simulation results. Therefore, it is necessary to take the different characteristics (r-values) in the rolling direction and the transverse direction into account. In addition, it is important to use experimental material data instead of stress-strain data calculated from numerical n- and K-values.

The choice of the hardening law affects the simulation results and therefore a study of suitable parameters for mixed hardening is needed. It is also necessary to verify this by experiments. Since springback behaviour depends on the stress-state after forming, it follows that the material model that can best predict the stresses is also the best for springback simulation.

This review reveals that small element size and slow punch velocity is necessary in order to achieve good results for springback prediction in automotive parts. These findings point out difficulties in the treatment of large automotive parts. Large models require rapid processing of huge amounts of data. Also the choice of material model is important. Geng et al. [50] showed that Barlat'89 model is more suitable for aluminium alloys. In paper F and G it is also shown that Barlat'89 model is suitable for HSS material.

6.3   Experimental assessment of surface defects

There are several ways to visualise surface defects. The most common in the automotive industry is to manually inspect the surface, either by stroking the hand over the surface or by application of a gloss and inspect the surface in a ramp of directed light sources. Then the defects are assessed by optical inspection, based on a master part which is the threshold limit for approval. This method demands highly skilled operators, which have the ability both to detect and classify defects. A more modern system uses non-contact measurements to detect surface defects.

6.3.1   Requirements on systems for assessment of surface defects

An evaluation system must fulfill several requirements, to help determine whether the part can be approved or not. The final goal is to have a system available for use in the production process for outer panels in the automotive industry. Some of the required criteria are listed below:

- Accuracy.
- Surface gloss.
- Visualisation.
- Facility of handling.
- Sensitivity to surrounding environment.
- User friendliness.
- The required measurement area.
- Demands on surrounding equipment.

Accuracy
In order to know the accuracy the system is to have, the size of a typical defect must be established. In paper G a test procedure is described which showed that a measurement system must have an accuracy to detect 10 μm in height difference in order to capture the smallest defects. Furthermore, the perception of a defect also depends on its shape and location, but a height of 10 μm gives an estimate of the required accuracy of a measurement system.

Surface gloss
The sensitivity for surface gloss divides available systems into two groups.

- Systems which need a highlighter.
- Systems which can measure directly on a sample.

The system which needs a highlighter has the advantage that it can also be used for measuring painted and polished surfaces, while the disadvantage is that the application of a highlighter is unfavorable due to its:

- being an extra procedure in the measurement sequence.
- being bad for the working environment.
- demanding care in application in order to give a layer of uniform thickness.

Visualisation
This is the key feature for a successful on-line assessment system. The evaluation of the results must be:

- easy to handle.
- give fast results.
- give a direct feedback of OK/NOK.
- accumulate results in order to provide a trend analysis.

Furthermore, it is important that the validation of defects correlates to the well established ocular validation scale and that the validation system is calibrated against the optical perception of the defect.

Facility of handling
Depending of the user demands, two types of system may be of interest:

- A system for use in a controlled environment (measurement room).
  Advantages: Higher accuracy, Better possibilities for automatic positioning.
  Disadvantages: Longer cycle time for measurements.
- A system for use in line production
  Advantages: Flexible, Short cycle time for measurement.
  Disadvantages: Lower accuracy, Lower grade of automatisation.

Sensitivity to the surroundings
Another important factor to take into account is the sensitivity to the surroundings. If the system is supposed to work in line production there are a number of possible disturbances: Varying background light, vibrations, oil and other environmental dirt, dust, temperature changes etc. These factors must not affect the system.

User friendliness
In order to have a fast validation system which can give fast responses to changes in the quality of the produced parts, a user-friendly system is necessary. This gives the operator time to react to changes in the production quality and generates less loss in scraped parts. The system should be based on maximum defects permissible. Below a certain criterion, the system should indicate an error, otherwise, the system should not give an indication. If only the defects which are bigger than the approved limit need to be evaluated, much operator time can be saved.

The required measurement area
Most of the non-contact systems have a relationship between accuracy and measured area. Therefore, it might be necessary to take several images and overlay them, in order to cover the area of interest. This demands that the images can be positioned quickly and accurately so that they overlap correctly. Obviously, the fewer images needed, the faster is the cycle of measurement. One way to avoid this complication is to assess a master of the whole surface, then define areas where defects will appear and concentrate measurements to these areas.

Demands on surrounding equipment
Different solutions demand different additional equipment. E.g. a line-based system may need only a fixture with defined camera positions, while a measurement room-based system needs a positioning system, e.g. a robot or the like.

6.3.2 Non-contact methods

Several systems are available, which can detect the defects that we classify as unacceptable surface defects. However, the *assessment* of the surface defects is the most difficult problem to be solved. The numbers of installations in the automotive industry are few, but these systems are being further developed and the automotive industry has started to use them as a help in the inspection process. In this study a system developed within the Volvo Cars Corporation (VCC), WMS [8], was used. In paper G both a test-panel and a door of a Volvo S40 have been studied and the results have been compared to a commercial system, D-Sight [5]. An example of the results can be seen in figure 8.
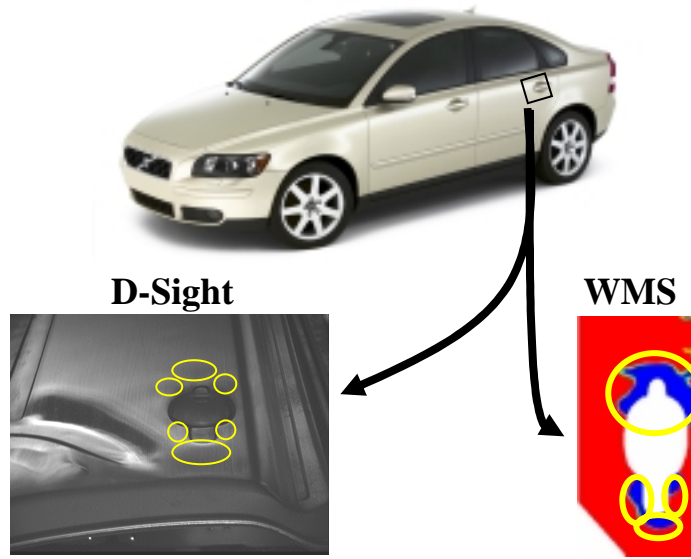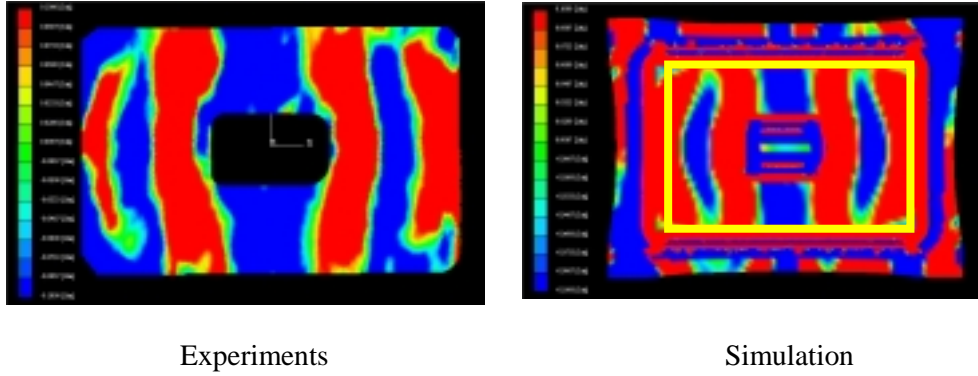
Figure 8: Evaluation of surface defects with D-Sight and WMS/NXT post processor. Depressions are marked with yellow circles.

6.4 Simulation of surface defects

The appearance of surface defects is closely related to the springback of a panel. Therefore it is important to have a correct springback prediction in order to have a good assessment of surface defects. The simulation of springback has been treated in section 6.2 and these results have been used in the evaluation of surface defects.

Previously, surface defects have been difficult to predict by sheet-metal-forming simulations. An interpretation of the results by strains and surface appearance was used for the prediction of the stability of the surface. Nowadays, tools for surface validation are available. With these tools, it is possible to detect the appearance of surface defects already in the design phase of a part and prevent the defects appearing, Hartung, [10] and Dutton, [67]. However, these studies did not correlate the experimental evaluation criteria and the numerical evaluation into the same validation tool as has been done in this study. In paper G the methodology for this is shown. An example of results can be seen in figure 9. The curvature is visualised by a colour change. This change corresponds to the blue and red areas in the WMS results where red corresponds to convex and blue to concave curvature.

Experiments   Simulation

Note: The area within the yellow box in the simulations corresponds roughly to
the area measured in the experiment.

Figure 9: Evaluation of surface defects based on FE simulation.

The same evaluation tool, NXT post processor [9], has been used for both the
experimental and the numerical results.

6.4.1   Conclusions

It is important to have the same evaluation criteria for simulation and
experimental assessment in order to correlate simulation and experimental results
correctly. However, estimation and a rough classification can be done by a
separate analysis. In paper G it is shown that there are working techniques for the
assessment and classification of surface defects by FE simulations by which the
evaluation of experimental and numerical results can be treated in the same
validation program.

7 Summary of papers

The interrelationships between the papers are illustrated in figure 10.
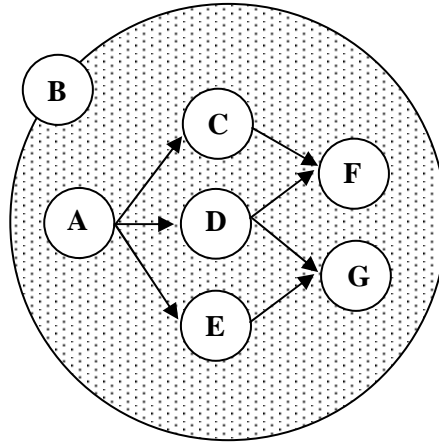
Figure 10: *Interrelationship between papers.*

Paper A identifies the research position. Paper C, D and E are all investigations to give basis for a good choice of parameters and models for evaluation of the answer to the research question:

How can FE simulation be used to improve the manufacturing process, in particular addressed to macro-geometric defects.

In paper F and G methods answering this question are suggested. Examples of macro-geometric defects are springback and surface defects.

In order to implement the results efficiently in production an efficient result- and knowledge transfer is necessary. This question is addressed in paper B, which provides the boundation for all the other papers on how to treat results.

Paper A: *Comparison of sheet-metal-forming simulation and try-out tools in the design of a forming tool*

Paper A describes a comparison of the use of try-out tools and the use of sheet-metal-forming simulation in the process of designing a forming tool. The emphasis is on the use of sheet-metal-forming simulation in particular. However, a critical issue is the "accuracy" of the results of these two techniques, in other words, how well each technique can predict or verify behaviour in real

production. The comparison between the two techniques was done with the aid of a Production Performance Matrix and the Production Comparison Matrix. The comparison showed that try-out tools have a wider range of parameters that can be studied with good accuracy. Sheet-metal-forming simulation offers a significant potential both to save time and reduce costs when the process parameters demonstrate good agreement between the simulation results and real production. Therefore, more extensive use of sheet-metal-forming simulation is recommended in the process of designing a forming tool.

Paper B: *Information Exchange within the area of tool design and sheet-metal-forming simulations*

Information exchange will be more and more important in the future. Old and new techniques will be combined in order to detect problem areas at an early stage in the tool design process and this increases the demand for reliable and effective information exchange. Paper B describes a method for handling information in a structured way to ensure easy access for the users. The information from FE analysis should be stored in a database that is readily accessible, for example from a portable computer. The information should be stored as animations that can be rotated and zoomed by the user. This contributes to shorter information paths, since an analysis of the results would not depend on the presentation of the interesting results in a report in paper format, or on the user's access to a post processor. Instead the potential user is able to analyse the areas of interest by studying the results first-hand.

Paper C: *Evaluation and comparison of surface defects on a simplified model for the area around the fuel filler lid by simulation and experiments*

The phenomena of springback and surface defects were tested using a double curved part. The design of the part was intended to generate surface defects (especially defects known as "teddy bear ears"). These defects were evaluated both numerically and experimentally. Paper C presents the simulation results in comparison with the experimental results generated by different measurement equipment. Since surface defects are a form of springback behaviour, it is important to consider the springback effect when predicting surface defects according to the results of sheet-metal-forming simulation. Due to the crucial influence of springback on the final quality of the part, a parameter study was done regarding some of the parameters mentioned in Section 6.2 above. It showed that it is necessary to use a precise tool description and a small element size of the blank. Convergent results were found for a relationship of 0.25 between the element size in the blank and the draw radius. This is a bigger relation factor than that found in the literature. However, it is much smaller than the one used in ordinary forming simulations, where a factor of 0.5 is common.

The surface defects were difficult to see due to the large amount of springback that distorted the surface. The deflections were better described as waves due to the springback than surface defects as "teddy bear ears". Furthermore, it could also be seen that while springback simulations were unable to predict the exact amount of springback, the simulations could successfully predict the correct trend toward springback in a given area.

Paper D: *Simulation and verification of different parameters effect on springback results*

Since the parameters have a great influence on the springback results, a study of various parameters was undertaken. As a test model a U-channel was chosen since it is an easy part to control both experimentally and numerically. A well-defined experimental process was used as reference for the numerical evaluation of the significance of the various parameters. Three material qualities were treated: mild steel, aluminium and extra high strength steel (EHSS).

The parameters analysed were: element size in tools and blank, forming speed, number of integration points through the thickness, contact damping, material model and hardening law.

The conclusion was that a suitable relation between draw radii and element size was 0.2, a suitable punch force 2 m/s, and 5 integration points through the thickness. Regarding the material model and material law, the best results were achieved with:
Mild steel – Hill'48 and mixed hardening [30/70], Aluminium – Hill'48 and mixed hardening [40/60], DP600 – Barlat'89 [100/0]

In the study several blank holder forces were used for each material. It was shown that an increasing blank holder force gave a decreasing springback for aluminium and EHSS but gave a constant springback for mild steel.

The simulations were calibrated to one blank holder force for each material. This parameter setting was then used for the other blank holder forces. The correlation was good between simulation and experiments for the calibrated blank holder force but as the difference in blank holder force increased, compared to the calibrated one, the accuracy in the springback prediction also decreased.

Furthermore, the stress oscillations were studied for a few elements and it was concluded that these have no effect on the results if only one element is observed. If the stresses are to be analysed, a larger area must be analysed.

Paper E: *Optimisation of draw-in for an automotive sheet-metal part – An evaluation using surrogate models and response surfaces*

Drawbeads are used for controlling the material flow during the forming process. The material flow is very important for the stress-field generated by the forming process. The stress-field is the driving factor for springback which causes surface defects. Therefore, the ability to give a correct description of the material flow, is of vital importance if the forming process is to be predicted accurately.

The drawbeads are described by a restraining force in FE simulations of sheet-metal forming. The restraining force depends on the geometry of the drawbead. Paper E presents a study in which optimisation was used for adjusting the restraining force to fit experimental measurement. A 2D-model was then used to calculate the drawbead geometry. The drawbead geometry was then compared to the physical drawbead and the results were found to be in good agreement.

My contribution was to perform the experimental tests and design the simulation model and methodology.

Paper E shows an efficient optimisation procedure for obtaining correct drawbead geometry in a sheet-metal forming process. In this study the draw-in was used as target value, but the optimisation procedure allows other constraints such as thinning and cracks to be added.

Paper F: *Numerical and experimental evaluation of springback in a front side member*

In order to verify the accuracy in springback prediction on an automotive panel a front side member was analysed both numerically and experimentally. In a well-defined process three different steel materials were studied, Mild steel, Rephos steel and TRIP steel. The geometry of the front side member is both complex (in the rear) and a simple U-shape (in the front). This is of interest in order to see how accurate a prediction can be obtained by FE simulations

The FE simulations were calibrated to the draw-in measured in the experiments and both punch forces and springback were compared. The springback was compared after trimming.

The results showed that FE simulations were accurate in the prediction of punch forces but exaggerated the springback (twist) in the part. Furthermore, it could be seen that the TRIP material showed significantly larger springback than the other materials. This is a very important observation and should be taken into account if TRIP material is to be used in automotive panels.

Paper G: *Evaluation and visualisation of surface defects on auto-body panels*

Surface defects are very difficult both to predict and to classify. Today, the classification of surface defects is based on subjective optical inspection, which uses reference parts as master. Furthermore, it is not possible to compare FE simulation with these optical classifications.

Paper G describes a method in which the same evaluation software is used in the classification of surfaces evaluated by both FE simulation and experiment. The classification of the surface defects is then based on the same criteria and are not dependent on the subjective evaluation, which is used today. The evaluation is based on curvature change, which is very sensitive to disturbances in the surface. A double curved panel and a rear door of a Volvo S40 were used for validation of the above method and of existing surface validation equipment. The results showed that the FE simulations and experimental results were in good agreement, and the results achieved with the new method were in agreement with the results found by the existing surface validation equipment. Furthermore, the study showed that the method described in paper G can be used for the evaluation of surface defects in automotive panels.

8 Discussion and conclusions

The research question was formulated as:

How can FE simulation be used to improve the manufacturing process, in particular addressed to macro-geometric defects?

The central part of this work is the development of a methodology for the evaluation of surface defects in automotive panels, both numerically and experimentally. There has for many years been a strong need for the ability to perform these kinds of analyses, but up to now there has been no solution to the problem. Also, relatively little work has been done in this area, in particular concerning coupling of results between experiments and FE simulations. In the developed methodology the same software is used for the evaluation of FE results as well as of experimental results. This opens possibilities for the evaluation of automotive panels with the same classification procedure both numerically and experimentally. Today, the evaluation is done by a subjective classification based on a master part which creates discussion of how the limits of "approved" and "not approved" should be interpreted. These discussions would be obsolete with the use of the methodology proposed in paper G. However, this presumes that the classification based on curvature change is correlated with the subjective scale used today.

The accuracy in the prediction of both springback and appearance of surface defects was in good agreement with the experimental results. However, the accuracy can be improved. In paper G both different material models and hardening behaviour were tested, with the conclusion that a better description of the material gives better accuracy in the results. It was concluded that Barlat'89 material model is preferable to Hill'48 and also that mixed hardening provides better results compared to isotropic hardening. However, it is difficult to supply input data for mixed hardening and therefore it is not widely used. An important task to improve the accuracy of the results, is therefore to develop a method whereby a feasible material characterisation of the hardening behaviour necessary a material can be given.

Regarding springback, it has been shown that a good accuracy can be attained with sheet-metal-forming simulations for experimental parts. However, when an automotive part was analysed, the results showed that the FE simulation exaggerated the springback. Since FE simulations for production parts are more complex than for experimental parts, the accuracy of the prediction will be lower due to both the complexity of the part and the difficulties to control the forming process in production. A clear indication of the sensitivity of the process parameters can be found in paper D where the same parameters were used in the FE simulations for a range of blank holder pressures. The results of the calibrated parameter setting gave good agreement between numerical and experimental results, but when the blank holder pressure was changed, the process conditions were also changed and the accuracy of the results deteriorated. This is due to the change in the process parameters e.g. friction, which was changed in the experiments but not in the FE simulations. In the forming process of a complex part the process conditions vary over the geometry of the part, while in the FE simulations simplifications are made e.g. a constant coefficient of friction is used, and therefore errors are introduced, which contribute to an error in the springback prediction. Furthermore, the results showed that TRIP700 generates much more springback than high strength steel and mild steel. It is very important to take this into consideration in the design of automotive parts where TRIP steels are used.

An important factor for the control of the forming process is the use of drawbeads. This has been treated in paper E where an optimisation method was developed. It showed good prediction of the drawbead geometry, compared to a physical tool, with a small number of iterations.

A method for handling results from FE simulations of sheet-metal forming was proposed in paper B. The method describes efficient and structured handling of information in order to ensure easy access to accurate and updated results for the user.

In order to analyse the correspondence between simulation and experiments and determine the significance of different parameters, the Production Correspondence Matrix (PCM) can be used (see paper A). This method allows the

user to examine a complex process and determine which factors are significant and are therefore important to study. PCM was used to determine important parameters to work with in order to improve the FE simulation of sheet-metal-forming, and the areas analysed in this work were identified as those with significant "gaps" (deficiencies) in correlation and therefore interesting to study more closely.

9 Further work

- Further evaluations of the accuracy in the springback predictions when using improved material data and material models.

- In order to have a validation system, which can be set in conjunction with the subjective scale for surface evaluation, the scale suggested in paper G should be correlated to the subjective scale used at the VCC.

- Further evaluation of the methodology and measurement equipment used in the evaluation of surface defects.

- Study the effect of the use of geometrical drawbeads in FE simulations on a deep drawn automotive part.

- Further numerical and experimental evaluations on other automotive parts.

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