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Finite Element Analysis of Sheet Metal Assemblies

Prediction of Product Performance Considering the Manufacturing Process

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Preface

The work presented in this thesis has been carried out at the Division of Solid Mechanics, Linköping University. It has been part of the SimuPARTs and SLSS projects, which were funded by the SFS ProViking programme and the following industrial partners: Volvo Car Corporation, Saab Automobile, Scania, Swerea IVF, Alfa Laval, Outokumpu Stainless AB, SSAB, Uddeholm Tooling, Sandvik Tooling and DYNAmore Nordic.

During the work that led to this thesis, several people have made important contributions and supported me. First of all, I would like to express my gratitude towards my supervisor Prof. Larsgunnar Nilsson for the trust in my ability to independently pursue my research and to the encouragement and guidance when it was needed. I would also like to thank my assistant supervisor Dr. Ramin Moshfegh (Outokumpu Stainless AB) for being straightforward with both critique and praise.

A number of representatives from industrial partners deserves credit for their efforts in realising experimental data for this work: Dr. Alf Andersson (Volvo Car Corporation), Per Thilderqvist (IUC Olofström), Jan Rosberg (Scania CV) and Peter Ottosson (Swerea IVF). All other members of the SimuPARTs and SLSS projects are also gratefully acknowledged for their support.

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Finally, thanks to friends and family for being there and to Lisa for pushing me and filling my life with joy.

Linköping, April 2014

Alexander Govik

Abstract

This thesis concerns the development of methodologies to be used to simulate complete manufacturing chains of sheet components and the study of how different mechanical properties propagate and influence succeeding component performance.

Since sheet metal assemblies are a major constituent of a wide range of products it is vital to develop methodologies that enable detailed evaluation of assembly designs and manufacturing processes. The manufacturing process influences several key aspects of a sheet metal assembly, aspects such as shape fulfilment, variation and risk of material failure.

Developments in computer-aided engineering and computational resources have made simulation-based process and product development efficient and useful since it allows for detailed, rapid evaluation of the capabilities and qualities of both process and product. Simulations of individual manufacturing processes are useful, but greater benefits can be gained by studying the complete sequence of a product's manufacturing processes. This enables evaluation of the entire manufacturing process chain, as well as the final product. Moreover, the accuracy of each individual manufacturing process simulation is improved by establishing appropriate initial conditions, including inherited material properties.

In this thesis, a methodology of sequentially simulating each step in the manufacturing process of a sheet metal assembly is presented. The methodology is thoroughly studied using different application examples with experimental validation. The importance of information transfer between all simulation steps is also studied. Furthermore, the methodology is used as the foundation of a new approach to investigate the variation of mechanical properties in a sheet metal assembly. The multi-stage manufacturing process of the assembly is segmented, and stochastic analyses of each stage is performed and coupled to the succeeding stage in order to predict the assembly's final variation in properties.

Two additional studies are presented where the methodology of chaining manufacturing processes is utilised. The influence of the dual phase microstructure on non-linear strain recovery is investigated using a micromechanical approach that considers the annealing process chain. It is vital to understand the non-linear strain recovery in order to improve springback prediction. In addition, the prediction of fracture in a dual phase steel subjected to non-linear straining is studied by simulating the manufacturing chain and subsequent stretch test of a sheet metal component.

Populärvetenskaplig sammanfattning

Simuleringsdriven produktutveckling möjliggör snabba och noggranna utvärderingar av både tillverkningsprocessers och produkters egenskaper. Standardförfarandet i simuleringsdriven produktutveckling har varit att simulera enskilda tillverkningsprocesser eller belastningsfall, men väsentligt större möjligheter fås om man simulerar hela processkedjor. Förutom att utvärdera en produkts kompletta tillverkningsprocess kan hela processens inverkan på den slutliga produktens egenskaper utvärderas. Om simuleringarna förutspår produktionsproblem eller om produkten förutspås ha egenskaper som inte uppfyller de ställda kraven så kan produktens konstruktion eller tillverkningsprocess förändras i ett eller flera steg för att se hur varje förändring påverkar den slutliga produktens egenskaper. Man kan på detta sätt spara mycket tid och pengar jämfört med om fysiska provverktyg och produkter skulle tillverkas, utprovas och sedan modifieras.

Den här avhandlingen behandlar utvecklingen av metoder för simulering av kompletta tillverkningsprocesser av tunnplåtskomponenter, samt studerar hur olika egenskaper utvecklas under tillverkningen och påverkar den tillverkade produktens egenskaper. I avhandlingen presenteras en simuleringsmetodik där varje steg i tillverkningsprocessen av en plåtsammansättning simuleras i sekvens. Den föreslagna metodiken har utvärderats och validerats på olika plåtsammansättningar och de virtuella och verkliga utfallen har jämförts. Variationer i egenskaper och processer förekommer i alla fysiska processer och det är därför viktigt att beakta dem när man utvärderar tillverkningsprocesser och produkter. Konsekvensen kan annars vara att en produkt tillverkas som virtuellt klarar alla krav men som efter den verkliga produktionen inte uppfyller kraven. I det här arbetet presenteras en metod som möjliggör variationsanalyser av hela tillverkningsprocessen för en plåtsammansättning.

List of papers

The following papers have been appended to this thesis:

- I. A. Govik, L. Nilsson, R. Moshfegh, (2012), *Finite element simulation of the manufacturing process chain of a sheet metal assembly*, Journal of Materials Processing Technology, Volume 212, Issue 7, pp. 1453-1462.
- II. A. Govik, R. Moshfegh, L. Nilsson, (2013), *The effects of forming history on sheet metal assembly*, International Journal of Material Forming, DOI: 10.1007/s12289-013-1128-9.
- III. A. Govik, R. Rentmeester, L. Nilsson, (2014), *A study of the unloading behaviour of dual phase steel*, Materials Science and Engineering: A, Volume 602, pp. 119-126
- IV. O. Björklund, A. Govik, L. Nilsson, (2014), *Prediction of fracture in dual phase steel subjected to non-linear straining*, Submitted.
- V. A. Govik, L. Nilsson, R. Moshfegh, (2014), *Stochastic analysis of a sheet metal assembly considering its manufacturing process*, Submitted.

Note

The papers have been reformatted to suit the layout of the thesis.

Author's contribution

I have borne primary responsibility for all parts of the work in the papers where I am the first author. The fourth paper was performed in collaboration with Oscar Björklund. However, I bore the primary responsibility for the forming simulations and Oscar Björklund for the fracture modelling part.

The work in this project has also resulted in the following paper which is not appended in this thesis:

- I. A. Govik, L. Nilsson, A. Andersson, R. Moshfegh, (2011), *Simulation of the forming and assembling process of a sheet metal assembly*, Swedish Production Symposium, SPS11, May 3-5, 2011.

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Part I

Theory and background

Introduction

Simulation-based design is a product development methodology that aims at minimising the physical testing of prototypes and manufacturing systems by using computer aided engineering (CAE) tools to evaluate the performance of a design, Bossak (1998). Finite element (FE) analysis is an indispensable CAE tool used to predict the performance of both the product and its manufacturing process. Different design options can be evaluated and compared, and the influence of different process parameters can be studied. Already in the early 1990's the automotive industry used FE simulations of sheet metal forming processes at tool and process design stages in order to predict forming defects such as wrinkling and tearing, see Ahmetoglu et al. (1994) and Makinouchi (1996). Since then, successful efforts in improving material models and improved computational resources have increased the accuracy of springback prediction. Much of the physical trial and error associated with tool try-outs have thus been replaced by simulations, saving both time and cost. According to Roll (2008) simulations had at that time reduced tool development time by 50 %. The increasing accuracy of forming and springback predictions has also led to efforts to extend the forming simulations to also include subsequent manufacturing steps. Chaining of the forming and the subsequent assembly steps is of special interest. The rationale for chaining the forming stage with the assembly stage is twofold. Firstly to support manufacturing system development and, secondly, to augment simulations of load performance with more appropriate initial conditions for the components, e.g. thinning, deformation hardened areas, and residual stresses.

The use of Advanced High Strength Steel (AHSS) in various structural components has increased the need for accurate simulations, since components made from AHSS demonstrate more severe springback behaviour than components made from ordinary mild steels. Even with support from FE simulation predictions, serious efforts are in some cases required to control the springback of a component made from AHSS. However, if the geometry and properties of the assembled structure can be predicted, estimates can be made as to whether the structure will meet its geometry tolerance even if one of its constituents fail to reach its initial geometry tolerance. In this way, time and effort can be saved. Moreover, by performing numerical robustness studies of complete manufacturing chains, the influence of material and process variables can be studied and the major sources of the products dispersion may be identified. Based on this information design changes can be

made in order to ensure that the specified requirements are fulfilled independently of all variations that may be present during manufacturing.

1.1 Scope and objective

The primary objective of this study is to develop and validate methodologies that enable efficient and accurate predictions of the properties of sheet metal assemblies. In order to achieve this, the manufacturing process must be considered since the properties of a sheet metal assembly depend on the virgin material properties of the sub-components and the manufacturing process.

In order to reach the objective, both overall simulation strategies and specific modelling methods are evaluated and developed. Part of the problem is to identify which processes that are reasonable to model in depth and for which processes more simplified models may be used. Some manufacturing steps involve substantial deformations and require advanced material models and solution techniques. However, the development of new material models is not within the scope of this work. Instead requirements of the material models will be identified and suitable existing models will be used.

In order to facilitate the applicability for industrial usage, the methodologies developed must be based on commercially-available software.

1.2 Outline

The organisation of the thesis is as follows. Chapter 2 gives an overview of important aspects on modelling techniques for simulations of different sheet metal manufacturing processes. Chapter 3 deals with material modelling, which is fundamental for the success of all simulations. In Chapter 4 a short description is given of the application examples used in this work. In Chapter 5 the papers appended are reviewed. In Chapter 6 important results and findings are discussed and conclusions are drawn. In Chapter 7 an outlook on future research topics is discussed.

In the appended **Paper I** a methodology for predicting the properties of a sheet metal assembly by the use of FE analysis is presented and validated. In **Paper II** further validation of the methodology is made by a sensitivity study in order to investigate the influence of history variables. In **Paper III** the unloading behaviour of a dual phase steel is investigated by a micromechanical approach. In **Paper IV** the prediction of fracture in a dual phase steel subjected to non-linear straining is studied. In **Paper V** a methodology for predicting the propagation of variations in a multi-stage manufacturing process is presented.

Manufacturing simulations

In this chapter, important aspects of modelling techniques for manufacturing simulations are discussed.

2.1 Sheet metal forming

Several forming methods exist for sheet metals e.g. drawing, flanging and stretching. The most common method, and the method studied in **Papers I and II**, is drawing. In a typical drawing setup, the sheet metal blank is drawn into the die cavity by a punch. Meanwhile, the blankholder exerts a normal force on the blank in order to control the flow of the sheet, see Fig. 1.

When the punch movement begins, stretching of the blank is initiated and as the blank flows across the die radius, it is subjected to bending. After the passage across the die radius, the blank is unbent and further stretched. At the bottom

Figure 1: Schematic view of a drawing operation including stress state in the blank.

position of the punch movement the geometry of the deformed blank closely corresponds to the tool geometry, but the stress state in the blank contains unbalanced stresses that creates moments, see Fig. 1. As the punch retracts and the blank is free from the die and punch constraints, the blank will springback due to its unbalanced stress state. The stress state is the combined result of a number of influencing factors e.g. the constitutive behaviour of the material, the geometry of the formed component and process parameters such as blankholder forces and lubrication. In order to simulate the sheet metal forming process using the FEM, both the forming process and the constitutive behaviour of the material have to be described by accurate models. The modelling of constitutive behaviour will be further discussed in Chapter 3, while the process modelling will be further discussed in the following section.

Forming simulation

Simulations of forming processes are extensively used in modern product development processes. At early stages they are used in order to evaluate the feasibility of the forming with respect to failure modes such as wrinkling, tearing and geometrical distortion caused by springback. At later stages different process parameters can be studied and optimised and the tool geometry can be compensated for springback, Burchitz (2008).

Forming simulations are often performed using explicit time integration. The explicit method is conditionally stable, but requires less memory and computations per time step compared to the implicit method. Explicit time integration is also well suited for the non-linearity of the forming process, e.g. contact constraints and material behaviour, since it lacks the convergence problems of implicit time integration. However, the refined meshes needed in forming simulations together with the critical time step of the explicit time integration can cause long computation times. This computation time can, however, be decreased by the use of mass scaling and/or an artificially high tool velocity, but care must be taken so that non-physical inertia effects exert a negligible influence on the solution. As a rule of thumb, between 100 and 1000 time steps per millimetre of tool motion are necessary, see Maker and Zhu (2000). For the simulation of the springback phenomenon, which is generally elastic, implicit time integration is commonly used.

Careful consideration should be given to the spatial FE discretisation of the blank i.e. what is termed as meshing. A sufficient number of elements must be used to resolve the stress gradient in the blank during the forming operation and to properly discretise the final geometry. However, computation time must also be kept reasonable. The element formulation chosen influences the spatial discretisation as well. The plane stress shell element is the most commonly-used element type in forming simulations, since it is more computationally efficient than a 3D solid element. From the plane stress shell element formulation it follows that the out of plane stress is negligible. Many recommendations concerning spatial discretisation

can be found in research literature. According to Li et al. (2002) it is reasonable to assume plane stress condition in a forming operation as long as the tool radius to blank thickness ratio is larger than five. Others have coupled the drawing tool radius to the blank element size, e.g. Lee and Yang (1998) suggested eight elements across the radius, while Burchitz (2008) suggested around 10 elements. However, these studies were performed using different types of shell element formulations.

The spatial discretisation of the tools also influences the quality of the forming simulation. Tools may be considered as rigid in most sheet metal forming operations. Consequently, only the tool surfaces need to be discretised. For the tools, a sufficient number of elements i.e. mesh density, must be chosen to approximate the curvatures of the tool. Too coarse a mesh can lead to deviations of the geometry and inaccurate contact forces. Lee and Yang (1998) found that at least 10 elements across a tool radius are needed.

In order to accurately resolve stress distribution in the through-thickness direction of a shell element, a number of through-thickness integration point layers is needed. Between five and nine integration point layers are sufficient to evaluate the forming stage, cf. Li et al. (2002), whereas the springback analysis may require more integration point layers. However, in literature the recommended number of integration point layers for springback simulations varies greatly. Li et al. (2002), and Wagoner and Li (2007) recommended 15-25 points depending on sheet tension and bending radius. Others found five or seven integration point layers sufficient, cf. Bjørkhaug and Welo (2004), and Xu et al. (2004).

A common FE solution technique in forming simulations is mesh adaptivity. The idea is that the mesh is adaptively refined in critical areas during the solution procedure. The most regularly-applied adaptivity method in forming simulations is the h-adaptivity, where an element is subdivided into smaller elements based on certain criteria. These criteria may, for example, be the angle change of an element surface or edge relative to the surrounding elements or adapting the mesh based on tool curvature when contact between tool and blank is approaching, what is known as look-ahead adaptivity. In the simulation of a drawing process, a high mesh density in the walls of the formed component will be achieved since the mesh of the blank will be refined when it is drawn across the tool radius. This dense mesh is superfluous for the subsequent springback simulation, and a coarsening of the component mesh may be performed prior to the springback simulation. Coarsening is a reversed refinement where several elements are merged into one element. One drawback of mesh adaptivity is that spurious stress concentrations may arise around nodes at connections between the different mesh sizes. FE meshes at different stages of a forming simulation are illustrated in Fig. 2.

Another important factor is the contact formulation. In order to achieve a correct stress state during the forming simulation, contacts should prevent penetration of the contact surfaces and achieve a correct pressure distribution. The pressure distribution is of great importance for the computation of friction forces. There are primarily two methods to include contacts in explicit FE simulations; penalty-based

Figure 2: *FE meshes at different stages of a forming simulation. Left: Mesh at the beginning of the forming simulation. Centre: Refined mesh at the end of the forming simulation. Right: Coarsened mesh before the springback simulation.*

and constraint-based algorithms. The penalty-based algorithm is computationally efficient and functions by placing interface stiffness's between the penetrating nodes and the contact surface. Consequently, minor penetrations will always occur since the contact forces are proportional to the penetration distance, cf. Oliveira et al. (2008). In contrast, the constraint-based algorithm will enforce the contact constraint exactly e.g. by using Lagrange multipliers to ensure the fulfilment of the constraints. However, constraint-based contact algorithms introduce difficulties when used in combination with rigid bodies and are rarely used in explicit FE solution procedures. A penalty-based contact algorithm is preferred in forming simulations due to its computational efficiency. One drawback of the penalty-based contact algorithm is that the accuracy of the solution depends on the choice of the penalty parameter, cf. Mijar and Arora (2000). The penalty parameter governs the geometry fulfilment caused by the penetration distance and also the friction forces which depend on the contact force. Friction is often assumed to follow Coulomb's law of friction i.e. to be linearly proportional to the normal force, i.e. contact force, with the coefficient of friction as a scale factor. Clearly the value of this coefficient will exert a major influence on the flow of the blank as well as on the tension in the blank, and thus also on the springback, cf. Papeleux and Ponthot (2002). The coefficient of friction is often assumed to be a constant value in the range of 0.05 to 0.2. However, it is known that, for example, local surface pressure and sliding velocity also affect friction, cf. Wiklund et al. (2009). In order to achieve correct local pressure in the FE simulations, it may be necessary to account for deformations of contact surfaces. For cases where the tool surface deformation cannot be neglected, contact pressure distribution may be significantly different from that in a rigid surface case. In Lingbeek and Meinders (2007), different methods aimed at

including tool deformations in forming simulations are discussed.

The coefficient of friction is difficult to measure experimentally. Experimental test conditions, e.g. contact pressure, sliding velocity, surface roughness and lubrication conditions, must resemble real forming process conditions. To add to the complexity of the problem, these conditions may vary depending on which region of the tool surface that is studied. A review of methods for friction modelling is found in Zmitrowicz (2010), and further information on friction and contact in a sheet metal forming setting can be found in Oliveira et al. (2008).

2.2 Sheet metal assembly

Sheet metal assemblies are a major constituent in a wide range of products; from cars and aircrafts to home appliances. As an example: according to Soman (1996) a generic automobile body consists of 300 to 350 stamped sheet metal parts, which are assembled using 60 to 80 assembly stations and 3500 to 4000 spot welds. An assembly station needs to be robust, meaning that it must maintain an acceptable performance level even though there may be a significant variation in the incoming parts. Hu et al. (2003) defined that a robust assembly station should absorb and reduce outgoing variation. However, achieving a robust assembly station is not an easy task. Apart from the incoming part variation that can cause misalignments or excessive deformation during fixturing, weld distortions may further add to the variation.

In an assembly station the assembly process can typically be divided into four steps called the PCFR cycle: *Place, Clamp, Fasten and Release*, see Chang and Gossard (1997) and Fig. 3. During assembly, components are first placed in the assembly fixture where their positions are secured by locators. Locators are features on the components and the fixtures that can be mated e.g. hole to pin, slot to pin and surface to clamp. The next step in order to complete the positioning of the components is to clamp them. Ideally, for nominal components in a nominal fixture, this step would not deform the components, but in reality components are often deformed during the clamping stage. After clamping, the components are fastened to each other. Most often this is achieved by a welding operation e.g. spot welding. In this case, further deformations are inflicted when the weld gun closes any remaining gap between the components. The final step is to release all constraints in the form of clamps and fixtures and let the assembly deform due to the unbalanced stress state caused by the assembly process. When equilibrium is reached, the stress state has been balanced, but large residual stresses may still be present in the assembly. These stresses may affect the behaviour of the assembly when loaded as well as its fatigue life.

Figure 3: *Illustration of the PCFR cycle.*

Simulation of assembly operations

When simulating the assembly process, decisions have to be made concerning the FE modelling approximations of the different assembly steps. In the following sections a short description of the simulation models used in this study is presented. The assembly steps are quasi-static problems, which are conveniently solved by an implicit FE methodology.

Positioning

The parts are positioned so that the holes and slots are aligned with their respective pin on the assembly fixture. However, appropriate boundary conditions are used instead of applying contact conditions between the pins and the components in order to avoid convergence problems. Penetrations are hard to avoid due to different mesh discretisation of the pins and the components. A gravity load is applied in order to ensure that the components are positioned as in a real case on the vertical supports. For larger, more flexible components, this gravity load will also cause deformation of the components and create a realistic initial condition for the subsequent clamping.

Clamping

A number of different techniques can be used to model the clamping operation. Boundary conditions can be applied directly onto the nodes of the flanges or on models of the contact surface of the clamps. The boundary condition may be either a prescribed load or a prescribed displacement. In this study, it was found that the most stable method was to use models of the clamps which are constrained to follow a prescribed displacement.

Clamping must be performed at several positions, and it can be performed in sequence or simultaneously at all positions. Due to the non-nominal geometry of the components, the misalignments during the clamping process may differ depending on the clamping sequence. If the physical process is conducted in a sequence, it must be considered whether the effect of this ordering is significant enough to be worth modelling. It will increase both pre-processing and computational time. However, if significant effects are anticipated, different clamping sequences can be evaluated and an optimal clamping sequence that minimises geometry deviation may be identified.

Welding

One of the most commonly-used methods to fasten components in a sheet metal assembly is resistance spot welding. A schematic overview of the process can be seen in Fig. 4. A weld gun exerts a force via two electrodes to close the gap and produce contact pressure between two sheets. Then a current is applied and heat is generated by contact resistance and the resistivity in the sheets. This initiates volume changes due to thermal expansion and also phase transformations in the material. The material in the contact zone melts and the two sheets are joined together. As the current ceases the electrode force is maintained for a cooling period to allow the material to solidify so that material separation is avoided.

The resistance spot welding process causes both mechanical and thermal deformations. Mechanical deformation due to the electrode force that closes the gap between the components. When the material is heated locally it expands and the surrounding material which is weakened by the high temperatures, may deform plastically. During the subsequent cooling the material contracts, which is influenced by phase transformations that occur in the material. This creates compressive stresses both in the radial and the circumferential directions at the edges of the weld, and in addition tensile stresses at the centre, cf. Nodeh et al. (2008).

The influence of thermal effects associated with welding is beyond the scope of this thesis. It is acknowledged that the thermal expansion and contraction occurring during welding will change the stress state and strength in the components, and thus the final geometry and residual stresses of the assembly. However, the modelling of the complex physical mechanisms during welding is not trivial. Detailed electro-thermo-mechanical-metallurgical 3D simulations and extensive temperature-dependent material data are required to accurately describe

Figure 4: *Schematic overview of the resistance spot welding process.*

how the residual stresses from previous manufacturing steps evolve during welding. Tikhomirov et al. (2005) presented simplified mechanical approaches that may be applicable to evaluate the distortion tendencies qualitatively, but not quantitatively. However, since no reasonably simple simulation method was found that quantitatively predicts the distortion and residual stresses, these effects are neglected in this work.

2.3 Chaining of manufacturing simulations

Historically, FE simulations have been used to simulate a single process. Due to the increased use of FE simulations in product development and the necessity of accurately predicting the performance of the product, coupled simulations of the complete set of manufacturing processes are becoming essential. In order to achieve this, the sequential nature of the manufacturing chain has to be acknowledged. That is, the resulting mechanical state of a component after a process step affects the next process step in the manufacturing chain. Hence, the results of each simulation step must be used as the initial conditions for the next simulation step. Consequently, the accuracy of each simulation step must be sufficient since errors are passed on to the next simulation step.

One essential factor in the chaining of manufacturing simulations is the information management i.e. understanding what type of analysis data is required, when it is needed, and in which format, see Åström (2004). The input and output data for FE software can often be represented in software-specific ASCII-files. These files facilitate the transfer of the results between different simulation models as well as between different softwares.

Simulation models of different manufacturing processes generally impose different requirements in terms of material models and spatial discretisations. The strategy concerning how the different simulations are to be coupled depends on how diverse these requirements are and on software capabilities. Basically, two options exist: consistent modelling or adaptive modelling. The consistent modelling strategy is

based on compiling the requirements in the different simulation models and choose appropriate model settings that can be used consistently throughout the simulation chain. The adaptive modelling strategy is based on choosing the appropriate model setting for each simulation model and translating the applicable results to the subsequent simulation model. Both methods have their merits and applicability. Consistent modelling makes the transfer between different simulation models simple, but computation time may be wasted due to excessively-detailed models. For adaptive modelling on the other hand each simulation is performed with an appropriate detail level but in the transfer between simulation models information may be lost e.g. when data are mapped between meshes with different element size or element type or when history variables are adapted to a different material model.

In the context of sheet metals, both strategies for coupling the different simulations have been utilised. The adaptive modelling strategy was used in Papadakis (2010) and Leck et al. (2010), where the forming simulations and the assembly process simulations were performed using different software and mesh discretisations. Special purpose mapping tools were used to transfer information between the simulation models. In contrast, Zhang et al. (2009) and Kästle et al. (2013) utilised the consistent modelling strategy where the complete FE meshes and forming histories were transferred from the forming stage to the assembly stage without any mapping. In **Paper I**, a procedure for simulating the complete manufacturing process of a sheet metal assembly was presented that was based on the consistent modelling strategy, see Fig. 5. The motivation for transferring the forming history

Figure 5: *FE simulation chain of the manufacturing process presented in Paper I.*

to the model for the simulations of the assembly steps is that the forming process alters the properties of the blank. The deformations during the forming stage

cause changes in thickness distribution and material properties. The deformation hardening expands the elastic domain of the stress state in the material, but at the same time residual stresses are retained in the component. Consequently, the evolution of properties alters the mechanical behaviour of the components when they are re-loaded and deformed. In **Paper II** a sensitivity study was performed in order to examine the influence of the forming history on the prediction of assembly properties. It is found that the residual stress state can exert a significant effect. Previously Kose and Rietman (2003) have shown that the forming history affects the deformation behaviour of a deep drawn component and Zaeh et al. (2008) have shown that the residual stresses from the forming stage affects the distortions due to a welding process.

The simulation of manufacturing chains research field is also active in applications other than sheet metals. A wide range of manufacturing processes have been simulated and presented in the literature, some of which are presented here. Hyun and Lindgren (2004) simulated the manufacturing process chain of a fictitious product. A billet made of stainless steel SS316L was forged, heat treated and cut. All manufacturing steps were analysed consecutively in one thermo-mechanical simulation by utilising an adaptive mesh technique. Pietrzyk et al. (2008) performed simulations of the manufacturing chain of a M14 bolt, which involved heat treatment, drawing, multi-step forging, machining and rolling. The complete chain was simulated by the FE software Forge 2005. In Werke (2009), the manufacturing process of three different forged components were analysed. Afazov et al. (2011) presented results from simulations of a simplified manufacturing process chain involving multi-scale data transfer for an aero-engine disc component. Two different FE programs were used for these process simulations. The macro scale process simulations included oil quenching, ageing and machining, while the micro scale process simulations included a chip formation model and shot-peening. The mapping and data translation between the different models and software were performed by a "finite element data exchange system", FEDES, presented in Afazov (2009). In Tersing et al. (2012) the manufacturing process chain of an aerospace component was simulated. The manufacturing chain included forming, machining, welding, metal deposition, and heat treatment. The simulations of the different manufacturing steps were performed with different models and FE software. A mapping tool was used to transfer information between the FE models and the FEDES software was used for translating information between the different program specific formats. Different material models were used due to diverse requirements in the simulations of the different manufacturing steps. However, Tersing et al. concluded that consistency in material modelling should be observed in order to achieve accurate results.

2.4 Variation propagation

Variation is an ever present nuisance in all kinds of processes. Sources of variation are usually categorised as either controllable factors or uncontrollable (noise) factors. For controllable factors the response of a pre-defined process with the same

input parameters is predictable and constant for consecutive trials. This does not hold for uncontrollable factors.

In a stamping process the variation can be classified into three components, cf. Majeske and Hammett (2003).

- *part-to-part*, is the variation that can be expected across consecutive parts during a given run;
- *batch-to-batch*, is the variation between different die set runs;
- *within batch variation*, is a measure of the process stability within a run.

Chen and Koç (2007) attributed the part-to-part variation to random variation of all uncontrollable process variables e.g. inherent equipment variation and blank dimension variation, within batch variation to the variation of controllable variables e.g. material variation and lubrication condition variation, and batch-to-batch variation to material differences between different coils and to differences in tooling setup.

In variation simulations of sheet metal assembly, three sources of variation are typically identified: part geometry variations, fixture variations and fastening tool variations, see e.g. Franciosa et al. (2011).

The manufacturing process of a sheet metal assembly can be generalised into a unit cell where a number of forming stages is followed by an assembly stage, see Fig. 6. Each forming or assembly stage can be further divided into individual manufacturing operations. Furthermore in the course of the manufacturing process of a sub-assembly, the generalised unit cell may be connected serially or in parallel with other unit cells. Each stage is characterised by an incoming entity (e.g. sheet metal blank or part), process variables (both controllable and noise) and an outgoing entity (e.g. part or sub-assembly). Variation is present both in the incoming and in the outgoing entities of a stage.

Figure 6: A generalised unit cell of the manufacturing process of a sheet metal assembly.

To account for all these variations in FE simulations, the variability of input parameters must be considered. The variability is formulated by associating a probability distribution with each input parameter and using an input sampling technique in order to generate a set of input parameters. The Monte Carlo method has been widely used for sampling sets of input parameters in stochastic analyses because

it is robust and easily implemented, cf. Haldrar and Mahadevan (2000). However, a pure Monte Carlo method requires a large number of sampling sets to reliably predict the mean and variance of a response. Consequently, Latin hypercube sampling (LHS), see McKay et al. (1979), is commonly used in conjunction with Monte Carlo analysis in order to limit the number of samples necessary. LHS divides the specified distribution of an input parameter into partitions with equal probability and randomly picks a value from each interval. This constrains the sampling to closely match the input distribution.

In a multi-stage manufacturing process, variations can be added and/or absorbed in each manufacturing stage, cf. Hu et al. (2003). In order to evaluate the end product variation, it is necessary to know how the variation propagates through the manufacturing process chain. In **Paper V** it is proposed that the variation analysis is segmented so that each manufacturing stage is evaluated individually using a Monte Carlo approach with Latin hypercube sampling, see Fig. 7. Succeeding stages make use of the pool of outgoing entities from the preceding stages. By segmenting the analysis it is possible to adapt the sample size based on the requirements of the current simulation so that each manufacturing stage is evaluated with an appropriate sample size. Moreover, the pre-processing task is somewhat easier when the simulations in the manufacturing chain do not need to be fully coupled and automated as would be the case if the entire manufacturing chain were to be evaluated in one variation analysis. However, a segmented approach will make contribution analysis difficult, since information about the influence of each variable on the response of a stage will be lost to the succeeding stages when segmenting the variation analysis. The only information available in the sampling of the succeeding stage is the serial number of the outgoing entity and this serial number is completely uncorrelated with the variables and the responses, due to the stochastic sampling. One way to retain a small amount of information is to re-organise the pool of data so that the serial numbers in the data pool are numbered in the order of a characteristic variation measure. Using this method an approximation to the influence of that variation in the succeeding stage is obtained.

Figure 7: A visualisation of the variation analysis using the presented methodology for a fictitious manufacturing process.

Material modelling

Material modelling aims at describing the mechanical behaviour of a material during loading. Phenomenological material models are often the most efficient approach, however material models based on, for example, crystal plasticity also have their uses, see e.g. Asaro (2006). A phenomenological model relies on analytical equations to describe experimental findings from macro scale tests. The complexity of material models may range from a simple linear elastic assumption to complex models describing several material phenomena in detail. The level of complexity is governed by both the accuracy level required and the intricacies of the load case and material response. The forming of sheet metal has been the most severe load case in this study. In the context of sheet metal forming, in-plane stresses dominate and a plane stress condition is often assumed in order to reduce the computational cost relative to the cost of a full 3D case. During a forming process the sheet metal is subjected to large deformations and, in many processes, also cyclic loading (bending-unbending). In order to accurately describe the evolution of plastic strains and the associated stress state during these loading conditions, a number of phenomena need to be addressed. This chapter is divided into sections describing some of the more important aspects related to material modelling of sheet metals subjected to large deformations.

A fundamental constituent of an elasto-plastic material model is the yield function, f , and the associated yield criterion

$$f = \bar{\sigma} - \sigma_Y \begin{cases} < 0, & \text{elastic} \\ = 0, \text{ and } \dot{f} = 0 & \text{plastic flow} \\ < 0 & \text{elastic unloading} \end{cases} \quad (1)$$

where $\bar{\sigma}$ is the effective stress, and σ_Y is the current yield stress. The yield function can be described as the surface that encloses the elastic region in the stress space. When the $f = 0$ criterion is fulfilled, the elastic limit has been reached and plastic flow may begin. For a material obeying an associative flow rule, the direction of the plastic flow is determined by the gradient of the yield function.

3.1 Plastic anisotropy

Cold rolling of sheet metal produces a material that possesses different properties in different material directions, i.e. anisotropy. The principal material axes of orthotropy coincide with the rolling direction (RD), the transversal direction (TD), and the through-thickness direction (ND) of the sheet. Plastic anisotropy is characterised by different sets of yield stress and plastic flow in different material directions. The anisotropic plastic flow is conveniently described by the Lankford parameters, r_α , which are usually determined from uniaxial tensile tests in different material directions. The Lankford parameter is defined as the ratio between the logarithmic plastic strain-rate, $\dot{\epsilon}^p$, in the width and thickness directions, i.e.,

$$r_\alpha = \frac{\dot{\epsilon}_w^p}{\dot{\epsilon}_t^p} = \frac{\dot{\epsilon}_w^p}{-(\dot{\epsilon}_l^p + \dot{\epsilon}_w^p)} \quad (2)$$

where the sub-index α denotes the material direction, and the logarithmic strain sub-indices l , w and t denote the longitudinal, width and thickness directions of the test specimen, respectively. In an isotropic material, all Lankford parameters are equal to one. In addition to anisotropy, the Lankford parameters can be used to assess the deformation behaviour of the sheet. Values higher than one indicate better formability since the deformation mostly takes place in the plane, which consequently reduces thinning, cf. Marziniak (2002).

If an associated flow rule is used, both the anisotropic yield stress and the anisotropic plastic flow can be described by an anisotropic effective stress function $\bar{\sigma}$. A number of anisotropic effective stress functions have been presented in the literature. The first of these was the Hill'48 function, see Hill (1948), which is an anisotropic extension of the isotropic von Mises effective stress function. It requires three anisotropy parameters and has gained much use in industrial applications. Among various other yield criteria, the three parameter YLD89 function used in **Paper V** could be mentioned, see Barlat and Lian (1989). This function has an exponent which strongly influences the shape of the yield function. An exponent value of 6 is often used for materials with body-centred cubic (BCC) crystal structures and 8 for materials with face-centred cubic (FCC) crystal structures, cf. Hosford (1993). In the case of plane stress and an exponent value of 2, the function is equivalent to the Hill'48 function. The three Lankford parameters r_0 , r_{45} , and r_{90} are usually used to calibrate the anisotropy parameters in the Hill'48 and YLD89 yield functions. As a consequence, the anisotropy of the yield stresses are determined from the yield function instead of from the yield stresses already experimentally determined. This generalisation may be incorrect since the anisotropy of the plastic flow is not necessarily equivalent to the anisotropy of the yield stresses. In order to address this drawback, Barlat et al. (2003) developed the more advanced eight parameter YLD2000 function. This function can be calibrated by the Lankford parameters and the yield stresses in three directions and the biaxial yield stress and biaxial Lankford parameter. Later, Aretz (2004) and Banabic et al. (2005) independently proposed their eight parameter functions, denoted YLD2003 and

BBC2003 respectively. However Barlat et al. (2007) showed that these two functions and the YLD2000 function were different formulations of an identical yield surface. In **Papers I** and **II** the YLD2000 function is used and in **Paper IV** the YLD2003 formulation is utilised.

A comparison between the above-mentioned effective stress functions and the isotropic von Mises function is illustrated in Fig. 8 for the mildly anisotropic DP600 steel. As can be seen, the greatest deviations between the anisotropic functions occur at the equi-biaxial point where the YLD2000 function benefits from having been calibrated at this point. As sheet metal forming processes generally create multiaxial stress states, a high level of accuracy for these load conditions is a desirable characteristic of the yield function. For more information on anisotropic yield criteria, a comprehensive review can be found in Banabic (2010).

Figure 8: *Yield loci for different effective stress functions in the in-plane principal stress space. The effective stress functions are normalised to the yield stress in the rolling direction $\sigma_{Y,ref}$.*

3.2 Plastic strain hardening

When metal is plastically deformed, dislocations in the crystal structure move and a gradual increase of dislocation density occurs. Dislocation tangles and pile-ups cause an increase of resistance to further dislocation motion and the metal is said to harden. This is often referred to as work hardening, since it is the amount of

plastic work that determines the increase in yield stress. However, other factors such as temperature and strain-rate may also affect the hardening, see e.g. Johnson and Cook (1983). For a monotonic loading process, the material model handles the hardening by an evolution of the yield surface following a plastic strain hardening function. The case of non-monotonic loading will be described in Section 3.3.

The plastic strain hardening characteristics of the sheet material are most often determined experimentally but there also are models based on dislocation theory, see e.g. Bergström et al. (2010). A uniaxial tensile test usually forms the basis of the characterisation, either directly from experimental data or by an analytical expression fitted to this data. However, in sheet metal forming processes the equivalent plastic strain often reaches values well beyond the strain at diffuse necking in a tensile test. There are several approaches used to extend the plastic hardening curve after diffuse necking. One approach is to extrapolate the tensile test data by using one of the numerous analytical expressions proposed in the literature, e.g.

$$\sigma_Y(\bar{\varepsilon}^p) = \begin{cases} \sigma_{Y0} + K(\bar{\varepsilon}^p)^n & \text{Hollomon (1945)} \\ \sigma_{Y0} + K(1 - e^{-A\bar{\varepsilon}^p}) & \text{Voce (1948)} \\ K(\varepsilon_o + \bar{\varepsilon}^p)^n & \text{Swift (1952)} \\ \sigma_{Y0} + K(1 - e^{-A(\bar{\varepsilon}^p)^n}) & \text{Hockett and Sherby (1975)} \end{cases} \quad (3)$$

In Fig. 9 the unreliable nature of extrapolation is illustrated. The analytical expressions in Eq. (3) are fitted to tensile test data of a DP600 steel and extrapolated beyond the point of diffuse necking. As can be seen, predictions of the hardening behaviour after diffuse necking vary considerably. This is a strong argument for the use of complementing experimental tests. Hardening of the material has a significant effect on the results of forming simulations, and thus also on the springback result.

Two additional curves that represent complementing experimental data are presented in Fig. 9. The curve denoted Aramis is the experimental curve obtained using the Aramis optical measurement system, which can evaluate the true strain relation in the diffuse necking zone and assess the corresponding true stress. Thus, information on the hardening behaviour after diffuse necking can be achieved. The other curve named "Merged" is obtained by an alternative approach. The hardening function is partitioned into two sub-functions i.e. the tensile test data are used up to diffuse necking and test data from a test able to handle higher strain levels are used after this. Shear and biaxial tests can typically handle at least twice the strain range compared to a tensile test. The shear test requires inverse modelling to extract the hardening curve, cf. Larsson et al. (2011), while the stress-strain data from biaxial tests may be used directly after a transformation into effective stress-strain values, cf. Sigvant et al. (2009). In **Papers I** and **II** the experimental

Figure 9: *Extrapolation of tensile test data using different hardening models compared to the merged curve of tensile test data and bulge test data.*

data was used directly, but in **Paper IV** an analytical expression was fitted for each partition of the experimental hardening curve.

For many metals, the stress response increases when subjected to an increasing strain rate i.e. positive strain rate sensitivity (SRS). Positive SRS acts as a regularisation during deformation and postpones strain localisation. The SRS is commonly accounted for as either an additive or a multiplicative contribution to the flow stress, cf. Larsson (2012). In **Paper IV** a multiplicative contribution to the flow stress was assumed according to

$$\sigma_f(\bar{\varepsilon}^p, \dot{\bar{\varepsilon}}^p) = \sigma_Y(\bar{\varepsilon}^p)H(\dot{\bar{\varepsilon}}^p) \quad (4)$$

where the SRS function H scales the plastic hardening. Many analytical SRS functions have been proposed in the literature, e.g.

$$H(\dot{\bar{\varepsilon}}^p) = \begin{cases} 1 + \left(\frac{\dot{\bar{\varepsilon}}^p}{\dot{\bar{\varepsilon}}_0}\right)^q & \text{Cowper and Symonds (1957)} \\ 1 + q \ln\left(\frac{\dot{\bar{\varepsilon}}^p}{\dot{\bar{\varepsilon}}_0}\right) & \text{Johnson and Cook (1983)} \\ \left(1 + \frac{\dot{\bar{\varepsilon}}^p}{\dot{\bar{\varepsilon}}_0}\right)^q & \text{Tarigopula et al. (2006)} \end{cases} \quad (5)$$

The SRS function proposed by Tarigopula et al. (2006) has been used in **Paper IV**.

3.3 Cyclic behaviour

During deep drawing, the sheet material is subjected to a number of bending and unbending cycles depending on the tool and drawbead layouts. This cyclic loading behaviour is the origin of several mechanical phenomena e.g.

- Early re-yielding (often referred to as the Bauschinger effect)
- Transient behaviour
- Permanent softening

see e.g. Yoshida and Uemori (2003) and Fig. 10.

Figure 10: *Schematic stress-strain relation for a tension-compression deformation.*

The Bauschinger effect is often attributed to microscopic back-stresses created by dislocation pile-ups. These back-stresses assist the movements of the dislocations in the reverse direction and lower the yield stress, see e.g. Banabic (2010). However, Kim et al. (2012) found that the interaction between ferrite and martensite phases in a dual phase steel was a major contributor to the Bauschinger effect. This is also supported by the findings in **Paper III**. In a material model, cyclic behaviour is governed by the hardening law which describes the evolution of the yield function. The hardening laws can be divided into three types: isotropic hardening, kinematic hardening and distortional hardening. Isotropic hardening expands the yield surface, kinematic hardening translates the yield surface and distortional hardening changes the shape of the yield surface. Isotropic hardening is unable to describe any of the phenomena listed that may occur during cyclic loading. Pure kinematic

hardening can describe the cyclic phenomena qualitatively but will yield poor results quantitatively, cf. Kim et al. (2006). However, by combining isotropic and kinematic hardening, i.e. mixed isotropic-kinematic hardening, accurate results can be achieved. The yield function is, in this context, more conveniently expressed as

$$f = \bar{\sigma}(\boldsymbol{\sigma} - \boldsymbol{\alpha}) - \sigma_{iso} \quad (6)$$

where $\boldsymbol{\sigma}$ is the Cauchy stress tensor, $\boldsymbol{\alpha}$ is the back-stress tensor representing the centre of the yield surface and σ_{iso} expresses the size of the yield surface i.e. the isotropic hardening.

Depending on the formulation of the kinematic hardening law, some or all of the phenomena listed can be described with good accuracy. One of the simplest kinematic hardening laws is the linear kinematic hardening presented by Prager (1949) and modified by Ziegler (1959). In a mixed hardening scheme the backstress evolution becomes

$$\dot{\boldsymbol{\alpha}} = (H' - \beta \tilde{H}') \frac{\dot{\bar{\varepsilon}}^p}{\bar{\sigma}} (\boldsymbol{\sigma} - \boldsymbol{\alpha}) \quad (7)$$

where β is the material constant that governs the linear mixing between isotropic and kinematic hardening and H' and $\tilde{H}'$ are the slope of the plastic hardening curve at the strain levels $\bar{\varepsilon}^p$ and $\beta \bar{\varepsilon}^p$, respectively. It requires the identification of one hardening parameter and can describe the early re-yielding and permanent softening but not non-linear behaviour. This hardening law was used in **Papers I and II**. In order to model the non-linear behaviour during cyclic loading, more elaborate hardening laws are required. The Armstrong and Frederick law is a non-linear kinematic hardening law, see Frederick and Armstrong (2007), that is able to describe early re-yielding and transient behaviour. It is used in **Paper IV**. The backstress evolution is given by

$$\dot{\boldsymbol{\alpha}} = C_X \left(Q_X \frac{\boldsymbol{\sigma} - \boldsymbol{\alpha}}{\bar{\sigma}} - \boldsymbol{\alpha} \right) \dot{\bar{\varepsilon}}^p \quad (8)$$

where C_X and Q_X are material constants. In Eggertsen and Mattiasson (2009) more hardening laws are reviewed from a springback prediction perspective.

Many of the hardening laws found in the literature require the identification of several hardening parameters. These can be determined from a cyclic test. Generally, tests for parameter identification should be able to handle loading conditions similar to the real problem studied. This is a problem for sheet metals since it is difficult to experimentally reach the compressive strain levels that may arise in a sheet metal forming operation. The conventional tension-compression test is unsuitable due to the buckling of the sheet. One improvement is to use an adhesive to bond several test pieces together to a laminate. In Yoshida et al. (2002) compressive strains up to 5 % were reached for a high strength steel using this test technique. Another test is the cyclic bending test, where an inverse analysis of the test is required to find the parameters. The exact test setup may vary, cf. Yoshida

et al. (1998), Zhao and Lee (2002), and Omerspahic et al. (2006). This test can reach compressive strains of up to 5 % depending on sheet thickness. However, this is still far from the large strains that can arise in a sheet metal forming operation.

3.4 Strain recovery

Studies have shown that the elastic recovery during unloading is nonlinear, see e.g. Zhonghua and Haicheng (1990), and that the apparent elastic stiffness degrades with increasing pre-strain, see e.g. Morestin and Boivin (1996). Springback, which is generally considered as an elastic recovery, will be considerably influenced by changes in the strain recovery behaviour. Consequently, these phenomena are important aspects of a material model used for springback prediction. The phenomena described suggest inelasticity but even so they are often referred to as a degradation of the Young's modulus or a degradation of the elastic stiffness. A more appropriate description could be the term unloading modulus, which is defined as the slope of a secant line between the starting and end points of the unloading curve.

Many explanations to the stated phenomena have been proposed in the literature. Zhonghua and Haicheng (1990) investigated dual phase steels and found that some of the ferrite enters into reverse yielding during unloading, leading to inelastic unloading. Cleveland and Ghosh (2002) and Luo and Ghosh (2003) explained the nonlinear unloading with dislocation pile-up and release. During release, the repelling dislocations push away from each other resulting in additional unloading strain. Since the dislocation density increases with increasing plastic strain, the unloading strain contribution also increases and causes a degradation of the unloading modulus for an increasing plastic strain. According to Halilović et al. (2009), damage mechanisms like porosity and void shape evolution can explain the degradation of the unloading modulus. In **Paper III** the explanation from Zhonghua and Haicheng (1990) was studied in detail using a representative volume element (RVE) of a dual phase microstructure. It was found that interaction between phases can contribute to inelastic responses well below the yield limit. During the loading of the micromechanical model, the strength difference of the ferrite and martensite amplifies the already-existing initial strain heterogeneity between the phases and the internal stresses. In the subsequent unloading, the martensite forces part of the ferrite into a reverse yielding, since the martensite has higher elastic deformation energy.

The degradation of the unloading modulus can easily be quantified by a uniaxial cyclic tensile test. In these tests, the specimen is loaded-unloaded at a subsequently increasing plastic strain, see Fig. 11.

A simple way to incorporate the degrading unloading modulus in a material model is to let the apparent Young's modulus decrease as a function of equivalent plastic strain. Yoshida et al. (2002) proposed the following equation, which has been used

Figure 11: *Results from a uniaxial cyclic tensile test with a close-up of an unloading-loading cycle.*

in **Papers I-IV**, to describe the decreasing apparent Young's modulus

$$E_u = E_0 - (E_0 - E_a)(1 - e^{-\xi \bar{\epsilon}^p}) \quad (9)$$

Where E_0 is the initial unloading modulus, which is defined to be equal to the virgin Young's modulus, E_a is the saturation level at an infinitely large plastic strain, and ξ is a material constant. Several other modelling approaches that take also the non-linear unloading into account have been presented, see e.g. Kubli et al. (2008), Sun and Wagoner (2011) and Eggertsen et al. (2011).

The apparent stiffness degradation is subject to recovery with time. According to Morestin and Boivin (1996) the unloading modulus will be recovered after 2 to 5 days depending on the type of steel. However, in Eggertsen et al. (2011) where the recovery of the elastic stiffness were measured by a vibrometric test, only partial recovery was found after two weeks for the steels studied.

3.5 Fracture modelling

During failure prediction it is necessary to separate the terms failure and fracture. Failure is defined as the loss of load-carrying capacity, while fracture is defined as material separation. Thus, failure incorporates the term fracture, but may also be caused by other structural phenomena which do not include material separation, e.g. material and geometrical instabilities. In sheet metal applications, thickness instability is a typical mode of failure. At a thickness instability, the deformation

localises in a narrow band which causes high levels of local strains and fracture is imminent. Instabilities arise when strain hardening can no longer compensate for the reduction in load-carrying area. Detailed FE models with elasto-plastic or elasto-viscoplastic constitutive laws can be used to capture the instability phenomena, see e.g. Moshfegh (1996) and Lademo et al. (2004).

Fracture can generally be either ductile or brittle. However, brittle fracture rarely occurs in sheet metal applications and thus this section will only cover ductile fracture. The ductile fracture process is characterised by initiation, growth and coalescence of voids in the material which causes a reduction of the load-carrying area and ultimately material fracture occurs. The reduction in load-carrying area leads to an apparent material softening. In damage models, this material softening is coupled to the constitutive relation, for example by the use of porous plasticity, cf. Gurson (1977), or continuum damage mechanics, cf. Lemaitre (1985). In a fracture criterion, on the other hand, this softening effect is not included in the constitutive relation. Instead fracture is assumed to occur first when a limit state is reached. Even though the fracture criteria are uncoupled to the constitutive law, it is convenient to consider them as a limiting state in a damage evolution process.

A fracture criterion can generally be expressed by an accumulating parameter, here denoted as the damage indicator D .

$$D = \int_0^{\varepsilon_f} f(\boldsymbol{\sigma}, \boldsymbol{\varepsilon}, \dot{\boldsymbol{\varepsilon}}, T, \dots) d\bar{\varepsilon}^p \leq 1 \quad (10)$$

where ε_f is the equivalent plastic strain at fracture, $d\bar{\varepsilon}^p$ is the equivalent plastic strain increment, and f is a scaling function that depends on internal variables such as stress state, strain state, strain-rate and temperature among others. The scaling function f is often normalised such that fracture is expected when the damage indicator D reaches unity. Several phenomenological ductile fracture criteria have been proposed in the literature. In **Paper IV** the capability of the following criteria was evaluated: Cockcroft-Latham (CL), Extended Cockcroft-Latham (ECL), Johnson-Cook (JC) and Modified Mohr-Coulomb (MMC). The MMC criterion was first presented by Bai and Wierzbicki (2010) for J_2 -flow theory, but in **Paper IV** the criterion was extended for use with an anisotropic effective stress function. The scaling functions of the fracture criteria studied are given by

$$f = \begin{cases} \frac{1}{c_1} \langle \sigma_1 \rangle & \text{CL, Cockcroft and Latham (1968)} \\ \frac{1}{c_1} \left\langle \frac{c_2 \sigma_1 + (1 - c_2)(\sigma_1 - \sigma_3)}{\bar{\sigma}} \right\rangle^{\bar{\sigma}^3} & \text{ECL, Gruben et al. (2012)} \\ \frac{1}{c_1 + c_2 e^{-c_3 \eta}} & \text{JC, Johnson and Cook (1985)} \\ \frac{1}{\bar{\varepsilon}_f^p(\boldsymbol{\sigma}, \boldsymbol{\alpha}, \dot{\bar{\varepsilon}}^p, c_1, c_2)} & \text{MMC, Paper IV} \end{cases}$$

(11)

where c_1 - c_3 are material parameters, σ_1 and σ_3 are the maximum and minimum principal stresses, $\eta = -p/\bar{\sigma}_{vM}$ is the stress triaxiality and $\bar{\varepsilon}_f^p$ is the equivalent plastic strain at fracture for a given stress state and strain rate. The inverse modelling technique is a suitable approach to calibrate fracture criteria, since not even the simple calibration test specimens experience constant stress triaxialities throughout their loading, cf. Björklund and Nilsson (2014). During different load paths the criteria accumulate damage differently due to their formulations. Irrespective of this, fracture criteria are often presented in a forming limit diagram (FLD) with a linear strain path assumption, where the fracture limit of a criterion is depicted as a line in the principal strain regime. The fracture criteria described are shown in Fig. 12 together with an experimentally obtained forming limit curve (FLC).

Figure 12: Representation of the fracture criteria in linear straining conditions in an FLD. The stress triaxialities of the load paths correspond to: uniaxial compression ($\eta = -1/3$), pure shear ($\eta = 0$), uniaxial tension ($\eta = 1/3$), plane strain ($\eta \approx 0.6$) and biaxial tension ($\eta = 2/3$). .

Application examples

In the course of this work three application examples have been used in order to develop, validate and exemplify simulation methodologies.

The Flexrail assembly

Figure 13: *Flexrail assembly (dimensions in mm).*

This application example was used in **Papers I** and **II**. The intention with the application example, see Fig. 13, was to validate the capabilities of the developed simulation methodology on an example that exhibits typical problems that may arise during the manufacturing of a structural assembly, e.g. in a car. The flex-rail tool presented by Andersson (2007), is used for the stamping of all three components. The flex-rail tool was originally designed as a semi-industrial benchmark tool that produces a sheet component with a complex springback behaviour including flange/wall angle changes, twist and sidewall curl. All these springback modes are characteristic problems found in a complex automotive component. The sheet components are made from 1.4 mm DP600 steel. Component 1 is the net shape

achieved by the stamping, while components 2 and 3 are the cut off ends from a stamped net shape component. The components are placed and clamped to each other in an assembly fixture and then they are joined by three spot welds at each flange. Geometry measurements of the components and the assembly were conducted using a coordinate measuring machine (CMM). Points along a number of lines in the width direction of the assembly were measured to find the cross-section geometries.

By using the Flexrail assembly, it was shown that accurate predictions of the assembly geometry were possible to achieve with the developed simulation procedure. However, the consideration of the full forming history was required in the simulations of the assembly steps in order to meet this accuracy.

Exhaust bracket

Figure 14: *Views of the exhaust bracket geometry during the process steps. From left to right: blank, after forming step 1, after forming step 2, and after fracture in the stretching test.*

The second application example was applied in **Paper IV**. The intention was to evaluate the accuracy of fracture prediction during complex loading situations. The example consists of the two-step forming operation of a sheet metal exhaust bracket and a subsequent stretching test of the formed component. Views of the exhaust bracket geometries during the process steps, from blank to fracture, are shown in Fig. 14. The exhaust bracket are made of DP600 steel with 1.5 mm nominal thickness.

By using the exhaust bracket, it was shown that an accurate prediction of the experimentally observed fracture was possible, despite the non-linear strain paths prior to fracture.

Cab suspension assembly

Figure 15: *Cab suspension assembly.*

The third application example was used in **Paper V**. The intention with this example was to perform a stochastic analysis of a complete industrial sheet metal manufacturing chain. The sheet metal assembly studied, see Fig. 15, consists of four individual parts. All parts are made from the low-strength forming steel DX53D, parts 1 and 2 with 3.0 mm nominal thickness and parts 3 and 4 with 2.5 mm nominal thickness. The basic outline of the sheet metal forming process of the parts is as follows: trimming, binder wrap, flanging and trimming. The assembling is performed at two stations. In the first station parts 1 and 2 are joined with four spot welds and in the second station parts 3 and 4 are joined to the first sub-assembly with seven spot welds each.

By using this assembly example, it was shown that reasonably accurate predictions of the final variation of the assembly were possible to achieve by performing variation analyses at each stage of the manufacturing process.

Review of appended papers

Paper I

Finite element simulation of the manufacturing process chain of a sheet metal assembly

This work demonstrates that it is possible to predict the final geometry of an assembled structure by the use of virtual prototyping. It is achieved by an FE simulation methodology to sequentially simulate each step of the manufacturing process chain. The result of each simulation step is transferred to the subsequent step. Thus, the evolution of deformations and residual stresses throughout the process chain can be predicted. Each step of the proposed methodology is described, and a validation of the prediction capabilities of the methodology is performed by comparing with a physically manufactured assembly.

Paper II

The effects of forming history on sheet metal assembly

In this study a simulation-based sensitivity study is performed in order to investigate the influence of the forming history on the properties of an assembly. In the study the assembly properties are predicted by sequentially simulating the manufacturing process chain of a sheet metal assembly. Several simulations of the assembly stage are performed in which different combinations of forming histories are transferred from the forming stage. It is found that the forming history affects the properties of the assembly and that the residual stress state is the most influential history variable. This demonstrates the importance of utilising the complete final mechanical state of each manufacturing step as the initial condition for the subsequent step in the manufacturing process chain in order to achieve accurate predictions of the assembly properties. Furthermore, if more reliable predictions can be made concerning the manufacturability of a product and its in-service behaviour, more design alternatives can be evaluated during product development while a considerably smaller number of physical prototypes are needed.

Paper III

A study of the unloading behaviour of dual phase steel

It is important to understand the strain recovery of a steel sheet in order to predict its springback behaviour. During strain recovery, the stress-strain relation is non-linear and the resulting unloading modulus is decreased relative to the virgin modulus. Moreover, the unloading modulus will degrade with increasing plastic pre-straining. This study aims at adding new knowledge on these phenomena and the mechanisms causing them. The unloading behaviour of the dual-phase steel DP600 is characterised experimentally and FE simulations of a representative volume element (RVE) of the microstructure are performed. The initial stress and strain state of the micromechanical FE model is found by a simplified simulation of the annealing processes. It is observed from the experimental characterisation that the decrease of the initial stiffness of the unloading is the main reason for the degrading unloading modulus. Furthermore, the developed micromechanical FE model exhibits non-linear strain recovery due to local plasticity caused by interaction between the two phases.

Paper IV

Prediction of fracture in dual phase steel subjected to non-linear straining

In this work, selected fracture criteria are applied to predict the fracture of a dual-phase steel subjected to non-linear strain paths. Furthermore, the effects of manufacturing history are studied. Four fracture criteria were calibrated in three tests using standard specimens. The fracture criteria were first validated using the circular Nakajima test. A second validation test case was included in order to validate fracture prediction for non-linear strain paths. In this test a sheet metal component was manufactured and subsequently stretched until it fractured. All criteria included in this study predict fracture during the Nakajima test with reasonable accuracy. In the second validation test however, the different fracture criteria show considerable diversity in accumulated damage during manufacturing which caused a substantial scatter of the fracture prediction during the subsequent stretching. This result shows that manufacturing history influences the prediction of fracture.

Paper V

Stochastic analysis of a sheet metal assembly considering its manufacturing process

During the manufacturing of sheet metal components and sub-assemblies, geometrical and mechanical variations are unavoidable realities. In this study, the variation of properties during the multi-stage manufacturing process of a sheet metal assembly is evaluated and the variability of a response due to loading is studied. A methodology to investigate how variations evolve during the assembling process is presented. The multi-stage assembling process is virtually segmented, such that stochastic analyses of each process stage are performed and coupled to succeeding stages in order to predict the variation in properties of the final assembly. The methodology is applied to an industrial assembly and experimental validations have been conducted. The prediction of the geometry of the final assembly is in good agreement with the experimental results, while the prediction of the variation of this geometry is in fair agreement.

Discussion and conclusions

In this work methodologies to predict the mechanical properties and geometry of sheet metal assemblies considering the manufacturing process have been developed and further extended to also include material and process variations. The accuracy of four fracture criteria was investigated when applied in manufacturing process simulations and subsequent load performance simulations. Furthermore, strain recovery has been investigated by studying microstructural related phenomena using a micromechanical approach. Understanding strain recovery is of utmost importance for the accuracy of springback predictions.

In each work of this thesis, the manufacturing chain was found to be an important aspect to consider. In **Papers I** and **II**, the forming history was shown to affect the succeeding deformation behaviour during assembly. In **Paper III**, the heterogeneous stress and strain state present in the material after the annealing process, was shown to affect the macroscopic elastic behaviour and the subsequent yielding. In **Paper IV**, it was demonstrated how the manufacturing process influenced the succeeding deformation and fracture behaviour. Finally, in **Paper V**, the variation in the manufacturing process was shown to influence the load performance of the final assembled structure. In all these studies, the succeeding simulation steps benefited from having inherited material properties and other initial conditions from preceding simulation steps. In these investigations, it was found that a simulation driven product development process must consider the manufacturing process in order to accurately predict the properties of the final product.

However, despite these findings, the importance of taking the manufacturing chain into account when analysing components during product development is not obvious in every case. In **Paper II** it was found that for a component with a simple geometry the influence of the forming history was minor, e.g. U-channel components or other geometries with straight wall sections. However, if the sub-component has a more complex geometry, e.g. regions with double curvature or other regions where large residual stresses may be retained, the forming history exerts a significant influence on the subsequent simulation results.

It is an ambitious task to model the entire manufacturing chain of a product and there are pitfalls that need to be avoided. First of all, when it comes to sheet metal forming there are still uncertainties on how accurately the springback is predicted. Despite substantial research efforts, all phenomena associated with springback are

not fully understood and phenomenological models cannot yet accurately describe all of them. One example of this is the non-linear strain recovery and the related degrading unloading modulus studied in **Paper III**. Thus, careful considerations must be taken in every application case as to whether the springback prediction can be trusted and used in subsequent simulations of manufacturing stages. Secondly, this approach requires substantial pre-processing and computational efforts. The trade-off between the necessary efforts and potential gains should be considered. Until more efficient simulation tools have been developed, this holistic simulation approach should mainly be reserved to parts or structures where experience indicates that manufacturing or performance problems are anticipated.

It is of great importance to reduce deviations from the nominal geometry. Optimisation methodologies can be applied in order to identify the correct process parameters and the correct tolerance settings of the manufacturing process of the assembly, and of its constituent sub-components. Optimisation methodologies may also be applied in order to reduce the geometry variation of the final assembly and to increase its performance. Further research is needed to analyse the effects of the clamping and spot welding sequences and to optimise the associated manufacturing process parameters.

Welding causes undesired phenomena, e.g. distortion, residual stresses, and changes of the microstructure. All these phenomena are important to reduce since they affect the properties of the assembly during the subsequent manufacturing steps, as well as the properties of the final assembled structure. It might be beneficial to incorporate the thermal effects of the welding in the simulation of the manufacturing process chain. However, the level of model complexity required for accurate results must be investigated. The challenge is to identify suitable simplifications which reduce model complexity to what can be industrially accepted.

This work has studied room temperature manufacturing processes however in many manufacturing chains one or several high temperature stages, e.g. hot forming and baking, may be included. How to facilitate the incorporation of simulations of these manufacturing stages in a simulation chain needs to be explored.

The apparent stiffness degradation investigated in **Paper III** is subject to recovery with time. However, some materials only experience partial recovery. Further research is needed in order to characterise and explain this phenomenon.

In **Paper V** a methodology for predicting the propagation of variations in a multi-stage manufacturing process was presented. However, weaknesses were identified in the contribution analysis which calls for further research. Methodologies need to be developed that improves the contribution analysis in the last manufacturing stage such that all stochastic variables in the entire manufacturing chain may be included.

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Part II

Appended papers

Papers

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