Loucas Papadakis

Simulation of the Structural Effects of Welded Frame Assemblies in Manufacturing Process Chains

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Preface

This thesis was authored during my occupation as a scientific assistant at the Institute of Machine Tools and Industrial Management (*iwb*) of the Technische Universität München. It documents the research results achieved during the INI.TUM Project “Simulation of the Joining Process by Considering the Effects of Forming and Spring-Back” funded by the AUDI AG and during my involvement in the Collaborative Research Centre Transregio 10 “Integration of Forming, Cutting and Joining for the Flexible Manufacturing of Light-Weight Frame Structures” funded by the German Research Foundation.

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Munich, June 2008 *Loucas Papadakis*

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Capital Latin symbols

symbol	**unit**	**denotation**
A	mm^2	cutting cross section
A	Nmm^{-2}	yield strength
A_0	mm^2	initial cross section of tensile specimen
A_1	mm^2	varying cross section of tensile specimen
A_{c1}	$°C$ or K	transformation start temperature
A_{c3}	$°C$ or K	austenite formation temperature
A_s	mm^2	theoretical cross section in area of cup side wall
B	Nmm^{-2}	hardening modulus
C	-	strain rate sensitivity coefficient
C_0	$Jmm^{-2}s^{-1}K^4$	radiation coefficient
dC^*	-	coefficient of deviatoric stress
E	Nmm^{-2}	Young's modulus
E_p	Nmm^{-2}	plastic hardening modulus
E_t	Nmm^{-2}	input tangent modulus after material flowing
$[D]$	Nmm^{-2}	thermoelastic-plastic stress-strain matrix
F	N	measured force during tension test
F_{bh}	N	force exercised by blankholder
F_{br}	N	breaking load
F_e	N	electrode compressive force
F_d	N	forming force exercised by punch
F_p	N	press force during extrusion moulding
F_y	-	yield function
$F(\dot{\theta})$	-	heating or cooling rate parameter
$\{F\}$	N	external nodal force vector
I	A	amperage of direct current

Index of Abbreviations

3D	three dimensional
AG	Aktiengesellschaft (Engl. plc: public limited company)
e.g.	example gratia, for example
cw	continuous wave
i.e.	id est, that is
min	minutes
Al	aluminium
ALE	Arbitrary Lagrangian Eulerian formulation
B	bake hardening steel
B	boron
BC	before Christ
C	carbon
Cu	copper
Mn	manganese
CAD	computer-aided design
CCT	continuous cooling temperature diagram
CNC	computer numerical control
CO_2	carbon dioxide
DFG	Deutsche Forschungsgemeinschaft (German Research Foundation)
DP	dual phase steel
FEA	finite element analysis
FEM	finite element method
FDM	finite difference method
FSW	friction stir welding
H xxx	steel alloy for forming with indication of its min. yield strength

1 Introduction

1.1 Motivation

Manufacturing processes are mainly used to machine, form or treat material into shapes that allow the creation of products with specific properties that fulfil certain functions. This use for manufacturing seems to have its antecedents in the ancient years, with an example being Homer's lively description of the fabrication of Achilles' shield in the rhapsody Σ΄, verses 473–482 (HOMER 800 BC). As the ancient Greek God of fire, Hephaestus was able to use his exclusive skills in the fabrication of Achilles' shield. The description of the shield (firm and robust, consisting of five metal layers made out of copper, tin, gold and silver) serves to highlight that innovating techniques such as the application of a combination of different metals in an integral construction in order to achieve the required material strength were already in use in the ancient years.

Following the numerous historical examples on ways to produce high quality light-weight frame structures in the automotive industry, even more demanding manufacturing processes have been adopted in the production lines in recent years. This attempt, along with the application of novel materials and construction methods, has increased the complexity of the entire manufacturing process chain and has contributed to reduce production costs. In order to achieve an optimised overall production chain, time-consuming adjustments of processes and products have to be done. In many cases, such efforts are based not on systematic methodologies, but on the know-how and expertise of technical personnel and, as such, are often not reproducible and documented. For this reason the demand for applying computer-aided methods to study the influences and effects of manufacturing tasks on machined structures has increased. Modelling methods may allow the process and structure engineers to investigate the processes, the product and the apparatus design in the earlier stages of product development, and may aid the search for ideal solutions. This aspect should be applied comprehensively in the whole production process chain in order to provide an optimised overall conception. Hence, computer-aided models and methods are needed to describe manufacturing processes and their interaction with the treated structure. Individual processes should be finally integrated into a sole virtual process system by means of a general computational method.

Engineers (= old French *engin* “skill, cleverness”, Latin *ingenium* “inborn qualities, talent”) have been challenged throughout the centuries to continuously develop new techniques (= Greek *tekhne* “art, skill, craft, method, system”) and machines (= Greek *makhana* “device, means”). And indeed this continuous technological progress is justified in the past years by the development of new materials and especially of high strength steels (SHIMITZU et al. 2004, KEEHAN et al. 2005, GARCIA-MATEO & CABALLERO 2005), along with innovative manufacturing and joining technologies, i.e. the hot forming (ÅKERSTRÖM 2006), the hybrid bifocal laser beam welding (TRAUTMANN et al. 2004) and the joining by electromagnetic tube compression (MARRÉ et al. 2004). Such innovations may lead to the production of accurate, high-quality products, reduce production costs, save energy due to light-weight structures, and assure the safety of end-users.

In order to describe complex manufacturing processes and their influence on the material, different models (= Latin *modulus* “measure, standard” or *modus* “manner, measure”) have been developed. Such models, i.e. mathematical relations, facilitate our understanding of the various observed physical phenomena, aid us in optimising the various procedures, as well as help us to experiment with the influence factors. As such, modelling is a fundamental element for the development of processes and products (LINDEMANN 2007). It is only with use of theses modelling methods that the complexities of modern production processes, including the design and construction of products and the product life cycle in general, can be handled (STEGER 1998). In the search for an optimised solution, time-consuming and cost intensive trial-and-error methods can be avoided by the application of suitable models (BAIER et al. 2004). Besides that, holistic models for describing the manufacturing chain of light-weight structures are applied during the process and during the product development (ZAEH et al. 2004b). Moreover, simulation methods may also be applied for supporting the design of mechatronic systems (REINHART et al. 2004).

As Figure 1-1 illustrates, in order to apply different numerical methods effectively, the relationships between these methods and experimental investigations should be clearly identified and defined. Hereby, based on the physical phenomena of processes and products, a mathematical abstract concept, i.e. model, is deduced. The abstraction level and, thus, the complexity of the model represents its completeness, its ambiguity, its application range and, most important, its validity for describing physical phenomena. Furthermore, the stability of procedures for solving numerical models is dependent upon the type of programmed algorithms, their performance and robustness, and their efficiency concerning the result accuracy and the required computation time. Based on this premise, the model and the computer analysis are defined and can be applied in order to describe the physical effects of idealised experiments or of prototype tests.

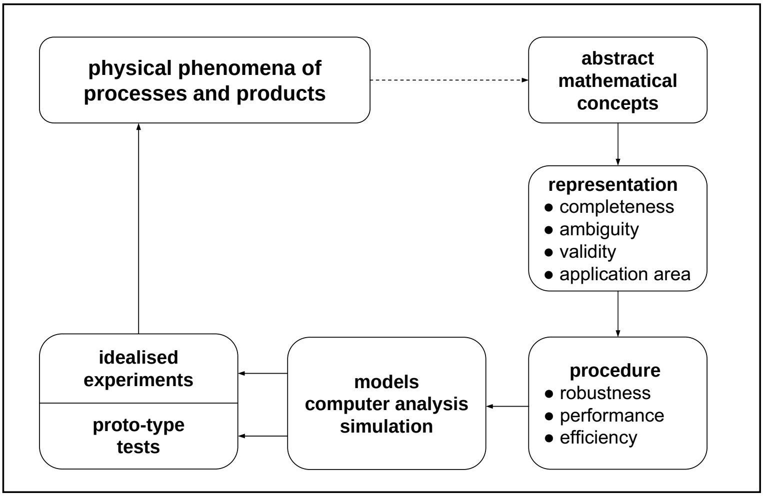

Figure 1-1: Relationship between the physical phenomena of processes and products, mathematical abstractions, computer analysis and experiments according to GOLDAK & AKHLAGHI (2005)

Experiments generally tend to fall into two broad categories. On the one hand, some are based on clearly understood theories, where a strong attempt has been made to exclude extraneous influencing factors. Relatively simple measurements of the Young's modulus or the thermal conductivity of a particular alloy represent this category. On the other hand, when experiments deal with complex phenomena that do not have a clearly understood theory, i.e. laser beam welding, a strong attempt is made to include any factor that may be relevant. Considering the capillar formation during the laser beam welding process is an example of this second category (AALDERINK et al. 2006). The above statements show that the abstraction or complexity level of models should be specially analysed in order to provide a suitable, efficient and reliable representation of the physical phenomena during manufacturing processes. Depending on the problem requirements, unnecessary effort can be avoided and only the essential effects are considered.

In recent years, not only models of individual manufacturing processes have become increasingly important, but also methods that consider holistic virtual manufacturing chains. Such methods, based on numerical models, accompany part of the product life cycle. Manufacturing processes change the geometrical, thermal and mechanical properties of material. They form it into a specific shape or machine it into a final form, or even improve the mechanical properties of the parts. In a final step joining techniques are applied to join component parts with each other providing semi-finished products or assemblies.

During manufacturing it is essential to achieve product accuracy and to follow and specify structural properties by way of computational methods. Furthermore, manufacturing processes and production systems can be pre-designed and optimised prior to prototype production for the needs of the production lines with the support of virtual simulative manufacturing chains (ÅSTRÖM 2004). This can improve the quality of the final product, save time and costs by avoiding trial-and-error during the process and plant design, achieve useful information about the behaviour of material during manufacturing, and supply valuable information on the interaction of process and structure.

Numerical solutions of manufacturing process chains strongly focus in supporting the production of frame structures in the vehicle industry. Frame structures play a central role in all means of transportation, dominating the total mass in automobiles, trains, aeroplanes and even space ships. In the case of automobiles, the frame structure mass constitutes about 30% of the total mass. In the case of the automotive industry, the mass-production, the high-quality standards and the need for mass minimisation all increase the necessity to enhance the virtual manufacturing methods in the production of frame structures.

Numerical methods may further improve the quality of parts and assemblies in relation to their geometrical and structural properties. In addition to geometrical accuracy of frame assemblies, crash requirements must also be fulfilled. Enhanced simulation methods may help to improve crash properties by considering the structural characteristics during manufacturing. Moreover, crash simulations reduce costs by proving the crash stability of vehicle structures prior to crash tests (CAFOLLA et al. 2003). Besides the constructive characteristics and material definition during the product development phase, manufacturing processes influence the strength of material and the stability of the structure, especially due to heat treatment. Such effects can, on the one hand, improve structural properties (due to the increase of the yield stress in case of heat forming) and, on the other hand worsen them (due to residual stresses after welding). Such material properties may be also predicted in advance by means of simulation methods (ERIKSSON et al. 2002).

The main fields of manufacturing processes in general, and in the vehicle frame structure production in particular, are forming, metal cutting and joining of metal alloys and composites (DIN 8580:2003, ZAEH et al. 2004b). Various forming processes may be applied depending on the construction, operational demands, and on production costs. Forming processes like deep drawing, extrusion moulding with reinforcing material, and hot or tube forming, influence the material and structural properties of metal parts. Material hardening and thinning due to the plastification procedure, and residual stresses in the structure after unloading (‘spring-back’), occur during the forming process of thin sheets. Moreover, in the case of hot forming of steel alloys, phase transformation takes place. All these effects have a significant influence on the structural behaviour of parts during the succeeding metal cutting and joining processes.

Material removal, process forces and heat input due to friction effects on the treated metal surface during metal cutting processes generate a new state of surface stresses and, thus, a new structural equilibrium follows, which may significantly influence the structure geometry (ÖZEL & ZEREN 2005). Joining technologies widely used in frame production are laser beam welding, resistance spot welding, MIG (metal inert gas) or MAG (metal active gas) welding, and the fairly new joining process of friction stir welding (FSW). Such welding processes are very efficient and cost-effective and show an excellent quality of the joints (XU et al. 2003, STEIGER et al. 2003). A disadvantage of these joining techniques, however, is the appearance of welding distortion and residual stresses in the structure due to heat and mechanical load effects, leading to a dimensional inaccuracy of the assembled components.

1.2 Scope and objectives of this thesis

The main objective of this work is to introduce a method of chaining the numerical analysis of the structural effect on frame components during successive manufacturing processes. The change of thermal, metallurgical and mechanical properties in a structure during manufacturing is thoroughly researched and analysed by applying theoretical reduced or advanced models depending on the difficulty of problem.

2 Fundamentals

2.1 General

This chapter presents an overview of the manufacturing processes involved in the process chain of frame structures of automobiles. This aids in the understanding of the physical phenomena, which occur during the production process of frame structures, and the identification of the influences of manufacturing processes on the treated structures. Special focus is given to the structural effects during and immediately after manufacturing processes. Furthermore, basic models are introduced, enabling the description of the structural effects in manufactured components. As outlined in Chapter 1, the preliminary forming processes considered are:

- deep drawing and
- hot forming of sheet metal components; and
- extrusion moulding of composite profiles.

In the area of metal cutting, the following processes are discussed:

- trimming by shearing and
- trimming by laser beam cutting in case of sheet metals; and
- milling and
- drilling in case of composite profiles.

Lastly, concerning joining techniques the following processes are presented in detail:

- laser beam welding;
- resistance spot welding; and
- friction stir welding (FSW).

Particular emphasis is placed on the physical laws and established material models describing the structural effects that are important for the model generation and the numerical solution of the system of equations (BATHE 1990).

Moreover, the fundamentals of numerical methods, which aid to describe the mathematical coherences of the phenomena occurring during manufacturing processes, are presented.

2.2 Manufacturing processes

2.2.1 Forming

2.2.1.1 General

Forming, also known as plastic deformation, describes the change of a given blank shape or a workpiece into a pre-determined form or a finished part (DIN 8580:2003). The grains are displaced in such a way that material cohesion and mass remain preserved. The forming processes are classified into the following groups according to the load, i.e. to the effective stresses, in the area of deformation (DIN 8582:2003): compression, tension, bending and shear forming. These groups are further sub-divided according to the relative movement between the tool and the workpiece, and to the tool and the workpiece geometry. These sub-groups consist of around 230 basic forming processes. Two or more processes may be combined simultaneously or successively within various operation steps. The form and/or the material properties change during each operation step.

Forming processes can be carried out at different temperatures. The temperature increase of the workpiece prior to forming processes causes the change of the material properties (e.g. reduce of yield stress by increasing temperature). This affects the deformation process and, additionally, leads to the heat treatment of metals, which may cause a strengthening of the material (ÅKERSTRÖM 2006).

In order to apply the theory of forming to real processes, an understanding of the crystalline structure of metals is essential. The smallest element of a crystalline structure is the unit cell. In metals, three basic forms of unit cells exist: the cubic, the tetragonal and the hexagonal. During the solidification of a molten material the unit cells are arranged parallel to each other forming solid areas (crystallites or grains), which are oriented randomly in relation to each other. The mechanical and physical properties of metals are determined by the length and diameter of the atoms, by their distance from each other, and by the concentration in lattices.

Thus, the properties of a crystallite depend on the orientation, i.e. they are *anisotropic*. However, in a composite of a polycrystalline material the individual crystallites statistically equalise each other, so that the material properties are approximately *isotropic* (LLEWELLYN 1994).

During plastic deformation of metals, lattices of unit cells are displaced in relation to one another. This displacement or *gliding* takes place mainly parallel to the lattice plane that has the highest density. However, in a polycrystalline material, which consists of a large amount of crystallites, the orientation of gliding planes occurs randomly. In this case, gliding is set independently from the direction of the load, since favourable gliding systems may exist. A large number of crystallites are arranged in such a way that a gliding in the force direction is not possible. Therefore, the metal workpiece's resistance of deformation is greater than that of a single crystallite (BARGEL & SCHULZE 2005). In order to describe the forming processes the *characteristic value of deformation* is introduced. During forming, the volume of the formed body remains approximately constant. For a cubic body with the initial dimensions, height h_0, width w_0 and length l_0, which is deformed into the final dimensions height h_1, width w_1 and length l_1 the following relation is applied:

$$V = h_0 \cdot w_0 \cdot l_0 = h_1 \cdot w_1 \cdot l_1 = const\,. \qquad (2\text{-}1)$$

There are various ways in which to express the degree of deformation described in the literature (FRITZ & SCHULZE 1998). The most representative is the logarithmic ratio of deformation φ given by:

$$\varphi_h = ln\frac{h_1}{h_0}; \quad \varphi_w = ln\frac{w_1}{w_0}; \quad \varphi_l = ln\frac{l_1}{l_0}. \qquad (2\text{-}2)$$

The relation of constant volume, given by equation 2-1, can be formulated in such a way (considering the formulation of the logarithmic deformation degree) that the sum of the orthogonal logarithmic deformation is equal to zero:

$$\Sigma\varphi_i = \varphi_h + \varphi_w + \varphi_l = 0 \qquad (2\text{-}3)$$

Thus, the change of material thickness, in case of sheet metal forming, i.e. deep drawing, can be determined according to equation 2-3.

Due to their crystalline structure, metallic materials show a linear behaviour in the stress-strain diagram up to the yield point (*Hooke's* law). The elastic deformation occurs due to reversible gliding, i.e. expansion or compression, of the lattices in the material structure. After reaching the yield point, an irreversible gliding of a larger number of lattices is observed (FRITZ & SCHULZE 1998).

In the case of homogenous materials, the favourable gliding plane is coaxial to the direction of the maximum shear stresses. However, a large number of one-dimensional failures in the lattice structure (dislocation) causes a reduction of the yield point for considerably lower shear stresses compared to an ideal lattice structure. *Mohr* states that in the case of a tri-axial stress condition, without considering the middle principal normal stress, the yield stress can be defined by:

$$\sigma_{\max} - \sigma_{\min} = 2\tau_{\max} = R_e = \sigma_v , \qquad (2\text{-}4)$$

where R_e is the yield point and σ_v is the uni-axial equivalent stress. The equivalent stresses can be calculated according to various theories such as the maximum normal stress hypothesis, *Tresca's* maximum shearing stress hypothesis, and *von Mises'* maximum energy of distortion hypothesis (GROTE & FELDHUSEN 2005). Figure 2-1 shows the influence of uni-axial and multi-axial states of stresses on the distribution of the shearing yield stress τ_F and the shearing strength τ_B.

There is a considerable risk of fracture above the point of intersection *S* by exceeding certain stress state in a multi-axial tensile stress. A higher level of deformability is achieved under multi-axial compression stress than under tensile stress described by the development of the shearing stress τ_B depending on the applied material. In the case of multi-axial tensile stress, exceeding the limits may cause cracking fractures.

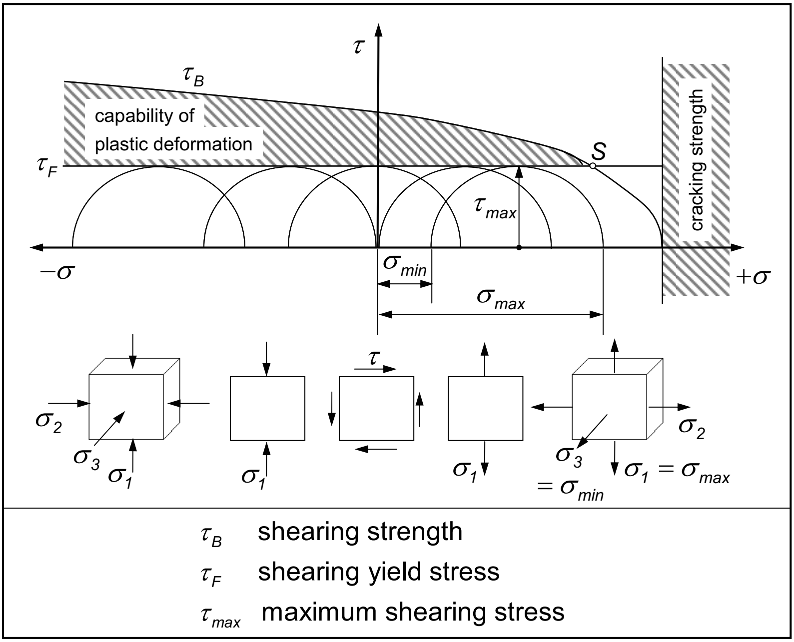

Figure 2-1: Mohr's circles of stresses for different load cases in a two-dimensional state of stress with maximum strength boundaries regarding the plastic deformation capability of material and the cracking formation according to FRITZ & SCHULZE (1998)

In the stress-strain diagram below (Figure 2-2), steel alloys with a relatively low concentration of carbon indicate a characteristic upper yield point R_{eH}. During the tension test, the tensile specimen experiences a continuous extension Δl and, thus, the measured force F and the tension stress σ increase. The nominal tensile strength R_m is reached at the point of the load peak. Since it is based on the initial cross section A_0 of the tensile specimen, the tension stress σ represents only a conventional parameter. The term k_f denotes the real yield stress, i.e. the deformation strength, and corresponds to the constricted cross section A_1.

3 State of Research and Deduction of Requirements for the Computational Chaining

3.1 General

In the previous chapter, the fundamentals of the various processes within the manufacturing process chain of frame structures were introduced regarding the process attributes, the influence on the structure properties of the treated components and, finally, of the finished assemblies after joining. Basic material models are presented, on which computational methods are established. Based on these perceptions, various simulation methods are introduced in order to solve specific problems during the manufacturing process or to predict structural behaviour of parts. In this chapter knowledge and applications of simulation methods concerning the manufacturing processes introduced in Chapter 2 are presented as a part of a holistic manufacturing chain. Moreover, recent developments in the area of computation and interlinking of different simulation steps for supporting manufacturing processes are discussed. Based on the existing methods and tools and on the increasing requirements on behalf of the industry concerning product quality and optimisation of the product development process, the need for further research is deduced.

The manufacturing process chain considered in this work includes, sequentially: the manufacturing fields of forming; metal cutting; and welding. The simulation of the structural effects along this manufacturing chain is introduced in this chapter, along with the latest research activities in the area of computational chaining methods during manufacturing.

3.2 Forming simulation

The simulation of forming processes is widely applied for research and industrial purposes. Simulation methods assure product quality and allow the determination of optimal values for the process parameters. Material failure (e.g. cracks or necking) and undesired form characteristics can be virtually predicted in advance and, thus, can be avoided during the real process. This can save time and minimise costs and, at the same time, help to optimise product quality. In recent years, the process simulation in metal forming reached the appropriate level for its practical application for industrial purposes. Simulating the complete forming manufacturing process prior to the real production process is, nowadays, state of the art (ROLL 2004).

The application of the finite element analysis for describing forming processes began thirty years ago. Since that time, a rapid development has been seen. In the last fifteen years, a large number of different studies concerning forming simulation have been performed, so that nowadays the development is at an advanced level with about fifteen commercial software codes worldwide, which enable the FEA of forming processes (ROLL & LEMKE 2005).

In the area of forming simulation a lot of two-dimensional analyses are still performed, since many forming processes can be reduced into two-dimensional models (plane or axis-symmetrical deformation condition). Three-dimensional models are increasingly applied, however, with the disadvantage of difficulties during the automatic mesh regeneration. In addition, long computation times are required, so that three-dimensional practical examples can only be used with a large computational effort. In the case of extrusion moulding of aluminium profiles, different simulation methods may be applied in order to describe the material flow and the structural properties. Moreover, the simulation of the extrusion moulding process of aluminium profiles with reinforcing steel elements has been developed further (SCHIKORRA 2006). Hereby, already established material and contact laws are applied.

Prediction and application capabilities of the forming simulation are shown in Table 3-1. Failure occurrences, such as cracks, wrinkles, and necking can be predicted with a high accuracy along with material flow, resulting sheet thickness, strain allocation, and blankholder pressing. With the aid of the process simulation of the deep drawing operation step the effort for die spotting can be reduced (HOFFMANN et al. 2006).

Due to the rapid development of forming tools and the drastic shortening of the trial-and-error method, the simulation of forming processes has already yielded a great reduction of costs. The support provided by simulation methods for designing the forming process and constructing and producing the forming tools reduces the product development duration tremendously. In the last few years, the development and production duration for the fabrication of the forming tools has been shortened to about 50%, and in the next few years a further improvement of 30% looks feasible.

prediction capabilities of the sheet metal forming simulation		
high precision	acceptable precision	low precision
• failure due to cracks • wrinkling in the forming area • thinning and strain distribution in formed sheet • material flow • blankholder pressing	• forming or die force • blank sheet entry in forming machine • initial blank contour • residual stress distribution • surface failure due to large strain • deformation due to spring-back effects	• surface failure due to high stresses • wrinkling in the area of contact restraints

Table 3-1: State of the art of prediction capabilities of the forming process simulation according to ROLL & ROHLEDER (2002)

The simulation of a forming process chain in successive operation steps including gravity, holding, deep drawing, trimming, folding and spring-back is applied widely in the automotive industry on different semi-finished frame structure components (ROLL 2004). However, additional development in this field is essential for a more accurate prediction of shape and residual stresses of formed sheet metal parts. For this purpose, the numerical compensation of spring-back has been developed and investigated by CHUN et al. (2002c) and ROLL & LEMKE (2005). Based on the compensation method described in sub-section 2.2.1.4 and on optical measuring systems, further strategies have been achieved and applied for prototypes (WEIHER et al. 2004).

The simulation of forming processes has reached a standard, which allowss the transfer of results into the digital planning processes of press shop tools. By employing digital methods, development processes may be included into the workflow of the sheet metal part production (KAMINSKY et al. 2002). Hereby, based on design models, the manufacturing procedure of a panel part in a press shop, including several process steps, can be described by means of computational methods. In this way, the construction of the press tool can be virtually optimised prior to the prototype manufacture. The linking of information concerning the virtual production with the planning related data – product, process and resource (PPR) – may be achieved in the future by applying an intelligent collective data management system. This would concern a large number of individual information, required in order to accomplish the computation and, later, the tool construction. Such information includes, among others, material properties, CAD geometry models of parts, formed geometries and FEM meshes, simulation results, press tool and machine CAD geometry and operational models.

However, by comparing the physical reality of a forming process with today's simulation models, it is observed that important influences on the forming process are not completely described, or are even neglected. Table 3-2 presents comparisons of reality and the common simulation models. In order to perform the forming simulation, the established approximation models have proven sufficient as far as the quality of results is concerned. For the exact computation of the spring-back effects, however, existing models should be enhanced. There is a particular difficulty in identifying which of the effects not taken into account may have a significant influence on the accuracy of the results. Thus, it is required to analyse different simulation approaches and validate their influence on the accuracy of the results. For instance, the implementation of the elastic properties of the die by BOGON (2003), and the enhancement of the forming simulation with the temperature variation by ROPERS (2001), aim to improve the accuracy of the computed stresses and, hence, of the spring-back behaviour of parts.

influencing factors	real process	simulation
production stroke rate	variable	neglected
machine	elastic	neglected
press tool	elastic	neglected, rigid
properties of die cushion	variable	neglected
friction coefficient	variable	constant
temperature	variable	neglected
topology of blankholder surface	variable	neglected
material	complex	simplified models
material properties	variable	constant

Table 3-2: Comparison of press machine, press tool and material properties in the real process and in the simulation according to ROLL (2004)

Initial investigations on the consideration of lubricant variation and on the development of a new friction-contact model are described by STEINICKE (2003) and BELYTSCHKO et al. (2002). In addition to this, the use of different material model definitions (LINGBEEK et al. 2007, BOUVIER et al. 2001) and the development of new material models (see sub-section 2.2.1.3) can lead to different results of the computed spring-back behaviour. Moreover, the optimisation of the numerical methods (i.e. solver type, time discretisation, element type) can contribute sufficiently to increasing the quality of the results without causing a significant increase of computation time (OLIVEIRA et al. 2002, REESE & LEPPIN 2004). The aspects presented above indicate that, in order to describe the process effects during forming more precisely and increase the accuracy of the results, there is a high demand for further and deeper computational investigation.

The process complexity during forming depends on a large number of factors including: the material properties; the lubrication; the forming machine; the tool; as well as peripheral and human factors. The high process complexity and the diversity of process characteristics imply high demands for simulation methods in order to describe such a holistic modelling system. Models and simulation tools can only describe the complexity of a process up to a certain point. Process effects based on microstructural phenomena and having significant influence on the global model may not be considered satisfactorily in the simulation. This leads to inaccurate results. Besides, the size of the workpiece to be computed causes enormous modelling effort and, thus, calculation time increases.

It is apparent from the afore-mentioned statements that the precision of deep drawn workpieces depends on various factors. The process stability may be determined by a number of additional influencing factors such as: the temperature; the tribology due to lubrication; the precision of the punch stroke; the die spotting procedures; the repeatability of material data of the coil and the geometry and positioning of the blank; and the process forces. These process parameters may cause quality defects in the form (e.g. buckle, dents or shape inaccuracy due to spring-back) or the surface (e.g. cracks). An extended study on the process influencing factors, and process control during deep drawing in different operation steps in the press shop, has been reported by HOFFMANN et al. (2007).

Based on the recent achievements in the area of forming simulation and the description of sequential steps within the forming process of metal frame components, the first calculated structural results of single formed frame components are provided for the further development of the computational chain.

4 Systematic Analysis of Models within Virtual Manufacturing Process Chains

4.1 General approach for the applied modelling methods

Available research results provide a wide spectrum of modelling methods and their applications for various welding tasks. The majority of modelling methods tend to be very strongly focused on individual aspects of the welding simulation and are often not considered as part of a holistic system. Especially, in the case of manufacturing process chains, partial models should be investigated as an element of the wider simulation system by preserving efficiency and quality as far as possible. The focus of this chapter is the analysis of different models for the simulation of welding, and the discussion and verification of their significance within the general manufacturing chain with the aid of elementary practical examples. The various influencing phenomena are categorised in different modelling levels or sub-systems in the simulation depending on the level of detail of the integrated simulation system.

Individual components, which are previously formed and machined, flow into the welding process carrying inhomogeneous structural characteristics and in some cases inaccurate geometrical shapes (due to spring-back). Such structural states of individual parts greatly affect the joined assembly behaviour during welding processes. The residual stress state and, thus, the geometrical shape of the entire frame assemblies depends on the preliminary manufacturing treatment of the components. The investigation of different thermal and mechanical influences within the welding simulation is based primarily on non-coupled (SYSWELD) and coupled (MSC.MARC) non-linear implicit solvers on the one hand, and on non-linear explicit solvers (LS-DYNA) on the other hand. Hereby, the structural and heat effects during welding processes are taken into account. By solely regarding their reactions on the manufactured parts, process-related influencing factors (e.g. energy efficiency and energy interaction with the structure in the weld seam area) are only partly considered within this approach.

4.2 Categorisation of simulation models

4.2.1 Classification of influencing phenomena

The main purpose of a simulation system for technical problems (i.e. for manufacturing tasks or for the strength of material) is to describe the relation between given and desired parameters. These parameters are related to each other by means of algorithms in case of the FEA. By means of the FEA a system of equations can be defined, the desired parameters can be determined and the effects of varying influencing parameters can be finally investigated. The understanding of this coherence, at least between the main features, is the major step in the simulation of complex process-structure phenomena of manufacturing processes. In this chapter, the modelling of these phenomena and their significance is classified in major sub-systems within a simulation system, considered as the central element for modelling the manufacturing process chain of frame structures. Initially, model generation is dependent on the applied computational algorithms. Thus, respective models can be specified by considering the relevant influencing process effects (e.g. the weld seam formation during resistance spot welding), the computational method or element type (e.g. application of shells) and their consequence on the calculated results (e.g. temperature distribution in the part) for a specific task.

Within the thermo-mechanical simulation of welding processes, the complexity of input and output parameters varies significantly. While the sought parameters (i.e. the results) of the simulation system are clearly defined (e.g. structural distortion, inner state of stresses, material hardening) from a mathematical point of view, the given parameters cannot be described completely. In order to characterise the influences on the results, the simulation system is classified into five modelling levels or sub-systems, here referred to as the geometrical system, the steady-linear system, the non-linear system, the transient non-linear system and the process-structure system. Similar hypotheses can be found in the work of ROEREN (2007). The method introduced in this thesis, is distinguished from the previous methods by concentrating its focus on the sequential increasing of complexity of the model by simultaneously testing and ensuring its quality and accuracy. A general approach to modelling different manufacturing processes by means of differentiating and reducing of influencing parameters (ROEREN 2007) is not the central aim in this thesis, but rather the continuous development of the different influencing phenomena within the computation chaining based on a systematic method, which classifies the simulation in different levels with increasing complexity.

The complexity of sub-systems increases successively following an inherit procedure, in which each system contains, in addition to its own influences, the ones of the subordinated systems. An exception is the geometrical system, which describes the fundamental level. Figure 4-1 shows an overview of the five sub-systems for the classifying process effects and computational methods along the welding simulation. The increasing complexity is described by means of different models with respect to specific welding processes as part of a holistic virtual manufacturing chain, which accompanies the process chain of frame structures.

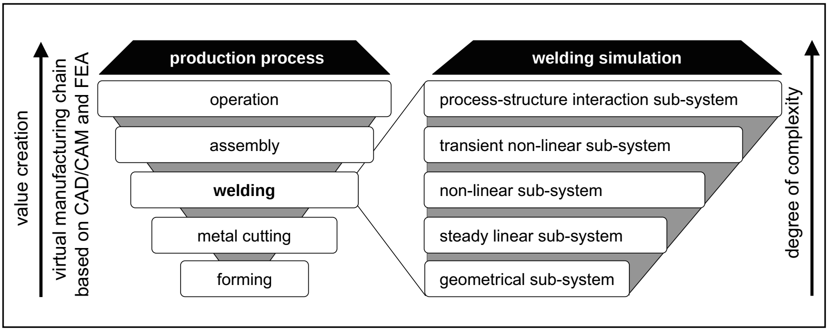

Figure 4-1: Welding simulation, classified in five modelling levels with increasing complexity, as a central element for the realisation of the holistic virtual manufacturing process chain based on CAD/CAM and FEA

As mentioned in previous chapters, there are a large number of models describing the heat effects of welding. Generally, such models can be divided into *reduced* and *advanced* models. Whereas the use of reduced models leads to rapid results describing tendencies, the advanced models aim to achieve accurate results. The investigations in this chapter tend to highlight the importance of both kinds of models for the simulation of welding processes, in order to achieve effective results depending on the modelling effort and the computation time. Examples for the integration of both reduced and advanced models by means of an efficient simulation are discussed for specific welding tasks. Figure 4-2 provides a detailed view of the influencing factors and physical phenomena divided into a thermal and a mechanical group, which are included in the successive modelling levels. Hereby, the increasing complexity of the various modelling levels, based on a simple geometrical definition up to a complex process-structure sub-system considering non-linear phenomena and structural effects due to preliminary manufacturing steps, is apparent. By means of this systematic classification of assembly models, the simulation of the structural effects along the virtual manufacturing process can be achieved.

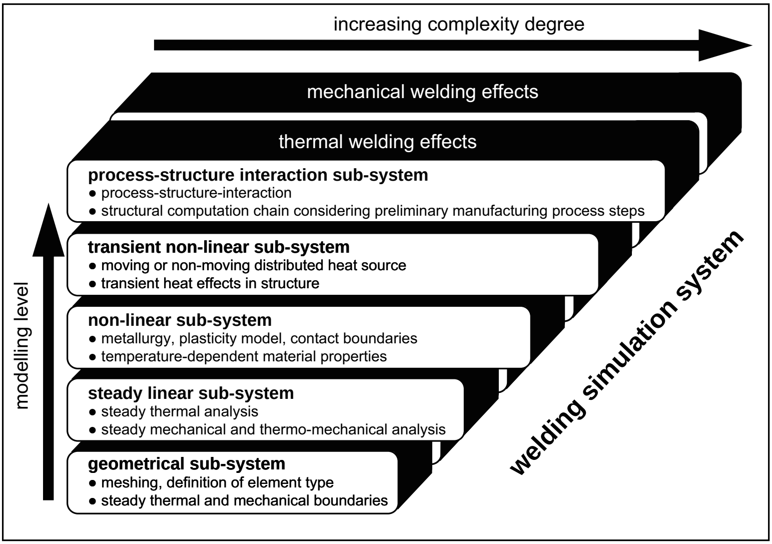

Figure 4-2: Classification of the welding simulation in modelling levels with major influencing phenomena for the successive realisation of the virtual manufacturing process chain

In the following, the sub-systems which describe the holistic system of a process-structure system are discussed in detail by means of model analysis and practical examples.

4.2.2 Geometrical sub-system

The geometrical sub-system is the basis of the structural FEA. Using a CAD-geometry in an initial state of model definition, the mesh of the structure can be defined by means of appropriate software (HYPERMESH, PATRAN). The mesh may consist of shell elements in the case of sheet metal parts or of solids in the case of compact geometries (i.e. joint nodes or cast components). A sample geometrical setup of a frame structure is shown in Figure 4-3. For certain manufacturing tasks, the definition of so-called hybrid meshes consisting of both shell and solid elements may be useful in reducing the total degrees of freedom and hence the computation time. For such geometrical models it is important to fulfil the conditions of the degrees of freedom for each element type. For this reason special transfer elements are defined in the intersection area of the element types in order to transfer the displacement tensors (rotational degree of freedom in case of shells), and thus the load tensors, on each element for all degrees of freedom (NÄSSTROM et al. 1992).

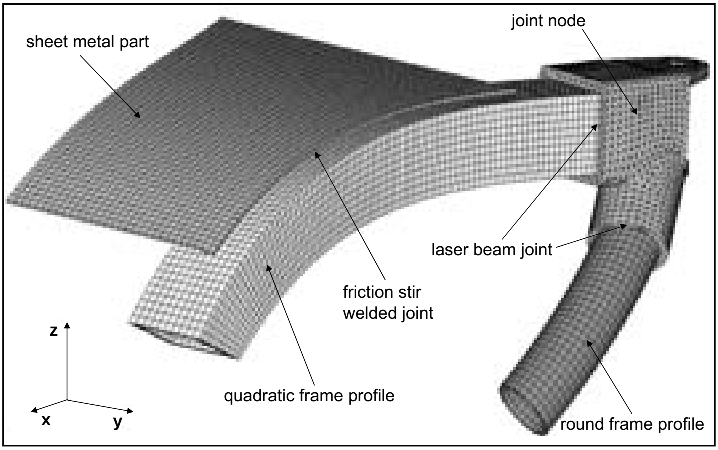

Figure 4-3: Mesh of an exemplary geometry setup of a frame structure assembly with different types of joints

When defining the geometrical system it is essential to prepare the mesh for the purposes of the simulation task. This means that the geometrical system depends on the degree of detail of the simulation system as a whole. Owing to its simplicity, a steady-linear calculation, described in sub-section 4.2.3, requires only a rather coarse mesh discretisation. In contrast, for a transient non-linear computation, described in sub-section 4.2.5, a very fine mesh discretisation should be defined in the area where large structural loads are expected. In the case of a laser beam welding task, for instance, rather thin weld seams are produced, requiring a fine mesh in the heat input area. Hereby, great temperature gradients due to heat input, material flow, residual stresses and phase transformation effects are expected. In Figure 4-4 the residual stresses in the weld seam area are illustrated for a resistance spot welding process of a lap joint of the mild steel 1.0338 (DC 04).

5 Virtual Chaining Method of Structural Effects of Sequential Manufacturing Processes

5.1 General remarks on chaining simulation results

The simulation chaining methods introduced in this thesis concentrate on two main manufacturing chains of frame assembly structures: the first is the treatment of sheet metals and the manufacturing of sheet metal frame assemblies; the second involves the manufacturing of composite light-weight frame profiles (also compare with Figure 1-2 on page 7). In the case of sheet metals the following manufacturing chain is considered: forming by means of deep drawing or hot forming; sequential trimming of the formed blank into the desired shape by means of shearing or laser cutting; and finally welding by means of resistance spot or laser beam welding. In the case of composite aluminium profiles the following manufacturing chain is studied: forming by means of composite extrusion moulding; metal cutting by means of circular milling or drilling; and finally welding by means of FSW or a hybrid bifocal laser beam. Along these process chains, structural effects which are changed during manufacturing tasks are calculated and interlinked with the following simulation steps of successive manufacturing processes. Structural effects studied within the developed chaining simulation method include: the residual stresses; the material hardening (i.e. the accumulated plastic strains); and in case of thin metal sheets, the material thickness. The calculated structural effects concern components after forming and metal cutting as well as entire assemblies after joining.

In the research work within this thesis, simulation results describing the structural effects during and after forming processes are provided in different file formats, depending on the software tools with which the computation was performed. Depending on the component to be investigated, the structural simulation chain can be realised in terms of shells (in the case of sheet metal frame components without reinforcement elements) and in terms of solids (in case of composite extruded aluminium profiles with reinforcement steel wires). In the latter case, residual stresses on the interface between the aluminium matrix material and the reinforcing elements along the material thickness vary significantly. Owing to this effect and to the additional material definition inside the extruded profile, the investigation of the structural effects within the manufacturing process chain of extruded aluminium components with reinforcing elements is performed by means of solid elements. The process and the calculation respectively involve a cooling down of the composite structure from the working temperature during composite extrusion. Based on these simulation results the simulation of metal cutting and welding can be successively performed. In this case the simulation chaining is applied within the simulation tools MSC.SUPERFORM and MSC.MARC.

Regarding the realisation of the manufacturing process chain by means of shells, the procedure was successfully enhanced by considering more than one component and, hence, providing the results of the structural behaviour of complete frame assemblies. The forming simulation was performed by means of different simulation tools (e.g. AUTOFORM, LS-DYNA or PAMSTAMP). Within the simulation chain, various calculated components in different file formats, including a deep drawing and a trimming calculation, were compiled in a common format based on the CAD geometry of the complete assembly carrying the preliminary structure properties. The positioning and the mapping operations were achieved with the aid of specific algorithms. Based on the complete assembly model, the succeeding welding simulation of residual stresses and distortions can be performed. Generally, such a method provides flexibility for the application of the simulation chaining of manufacturing processes and increases operator convenience. Thus, this method can be carried out efficiently when investigating the manufacturing process chain of real frame assemblies in the body-in-white assembly of the automotive industry.

The chaining method of computed structural effects during manufacturing processes is presented in this chapter. Structural results of frame components after computation of certain manufacturing steps (i.e. forming, trimming, etc.) were interlinked (i.e. mapped or projected) onto a new FE-mesh prepared for the next computation step, which satisfied the requirements of the manufacturing processes (see also sub-section 4.2.2). The results were converted into the required format for the purposes of the computation of the sequential manufacturing process. In cases of joining of more than one component in an integrated frame assembly, the source mesh was positioned on the target mesh in the coordinate system of the component assembly. For this task a coordinate transformation of the vector results (i.e. the stresses in each coordinate) was performed. Finally, the nodes and elements of the integrated model had to be renumbered in order to avoid duplications.

5.2 Mapping of simulation results

5.2.1 Structural simulation results

Single simulation methods of the forming process, of the metal cutting process and of the welding heat effects provide, in the first stage, the basis of the simulation chain, and may be performed independently by experts in a standard way without considering any special requirements due to chaining. This can help to avoid time-consuming misunderstandings and conflicts between company departments on the way to realising a virtual chain of products and processes. In this section the interlinking task of various simulation results is introduced.

In order to achieve the interlinking between structural simulation results, the following structural physical components were considered:

- nodal coordinate position and nodal deformation respectively;
- residual stresses;
- effective or cumulated plastic strains; and
- thickness variation (i.e. material thinning, in the case of sheet metals).

The manufacturing computation chain, when considering only a single component, i.e. not an assembly, can take place on the resultant geometry after forming or metal cutting. Thereby, the mesh can be prepared for the following simulation tasks or the mesh refinement operations can be performed during the calculation. A projection or mapping of the calculated results onto the new mesh with the same or similar geometry was performed prior to, or during the calculation, by averaging the simulation results of the original elements onto the target elements. The simulation chain can be performed on both solid and shell models depending on the model. A schematic workflow of the manufacturing process chain of single manufactured parts is illustrated in Figure 5-1. Here, the simulation of each manufacturing process consists of the geometry or mesh of the model and the structural results. A mapping operation after every simulation task is carried out on the remeshed model for the successive simulation. The total deformation between the initial and the final part geometry can be calculated and, thus, the dimensional inaccuracy behaviour along the manufacturing chain can be predicted. The knowledge and final geometry provided by the simulation chaining methods can flow back to the initial process step and be used in order to compensate for dimensional inaccuracies, for example, by digital die spotting within the forming simulation with the aid of the deformed shape of the part.

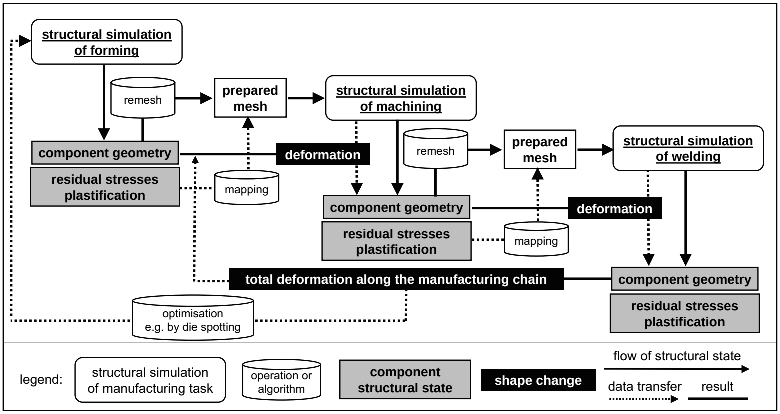

Figure 5-1: Structural simulation chain along the process chain forming-metal cutting-welding including model flow, data transfer and mapping between each simulation task and resulting deformation of the structure after every manufacturing step

The simulation chain method of single manufactured parts is presented by means of two basic geometries. The first example concerns a deep drawn steel cup which is successively trimmed to a certain shape and is welded with a bead-on-plate laser beam seam. The second concerns a basic extrusion moulded composite structure with an aluminium matrix and reinforcement steel wires cooled from the working temperature down to room temperature, then machined by means of a milling process.

5.2.2 Mapping of results within a shell model

The computational chaining of the structural effects along the manufacturing of the deep drawn cup is introduced here. The computational chaining method was accompanied by experiments on the real manufacturing process of this example. First, the deep drawn process of an 1.0338 (DC 04) mild steel sheet with a thickness of 1.2 mm was performed with the appropriate simulation using the FE-programme PAMSTAMP. Then, by laser beam cutting, the deep drawn sheet was trimmed to the target shape. This operation was also performed in a parallel fashion with the aid of a trimming simulation step by using the geometry contour of the desired shape in the form of a spline. The trimmed geometry of the cup was measured using a 3D optical system and was then available as a scatter-plot. Thereafter, bead-on-plate laser beam welding was performed, and the final geometry of the cup was digitised once more in order to determine the welding distortion. Transient measurements were also performed as described in sub-section 4.4.7. The regeneration of the mesh and the mapping of the results onto the new mesh followed the calculation of the spring-back. Finally, the interlinking of the simulation results into the welding simulation was performed and the simulation of the welding distortion with the FE-software SYSWELD was carried out on a shell model. It should be noted that the spring-back computation can be performed with the aid of advanced material models, such as those introduced in sub-section 2.2.1.4 as well as with an elastic isotropic calculation. At this stage, complex spring-back effects were not specifically investigated. References on such research activities were discussed in section 3.2. The main focus of this thesis is the chaining methodology and not the improvement of the computation of the spring-back effects.

Figure 5-2 illustrates the workflow for the virtual manufacturing chain forming-trimming-welding of a cup. This method allows for the chaining of the structural effects between different simulation tools and includes several different formats. For the realisation of the mapping and conversion functions, only linear shell elements with a maximum of five layers along the thickness and one integration point in each layer are available. For the successive welding simulation, the structural properties can be mapped on shell elements of higher quality (i.e. with four integration points in each layer of the quads). Such high-quality shells can increase the accuracy of the results during the computation of the welding heat effects. After trimming and refinement of the mesh the mapping algorithm was applied and the structural results were transferred onto the new target mesh. Finally, the results are imported into the software SYSWELD for further computation. With the aid of special sub-routines implemented in the Systus Interface Language (SIL) the sheet thickness was assigned on every element of the model. Moreover, the residual stresses and the strain hardening of the material were transferred into the thermo-mechanical computation with the aid of further sub-programmes during an initial computation step. Thus, it is important during this procedure to maintain the element numbering. The different sub-routines implemented with SIL, as well as further sub-programmes, for example for the conversions of the units of stresses, are presented in detail in the Appendix.

6 Application and Benefit

6.1 General

The previous chapters have presented an extensive investigation of the structural effects of frame assemblies during welding processes as a part of the integrated manufacturing chain in body-in-white assembly for different practical examples. Furthermore, a computational chaining method was introduced, which allows the transfer of structural results between different simulation steps along the virtual manufacturing chain. The knowledge gained from studying different practical cases was adopted to support real manufacturing tasks in the production of vehicle frame structures.

In the following, practical applications are introduced, which are computationally supported by the simulation chaining method. Thereafter, the benefit of applying the presented chaining method on examples of industrial relevance is discussed, and the general validity of the developed method is demonstrated.

The application examples deal with the manufacturing process chain of frame assemblies consisting of formed steel sheet metals for the body-in-white in the automotive industry. These investigations were performed within the scope of the INI.TUM research project in cooperation with AUDI AG (plc). Hereby, a sill board and side crash panel B-pillar welding assemblies were utilised based on shell models. The computational method was verified with measurements on real manufactured parts. A further application example is based on the sub-project C7 of the SFB Transregio 10, funded by the German Research Foundation DFG (Deutsche Forschungsgemeinschaft). The introduced method is demonstrated on a composite aluminium profile, which was formed by means of composite extrusion, and drilled and finally welded by means of friction stir welding. This task is part of the manufacturing process of an integrated vehicle frame structure, which is chosen as a demonstration example for the overall research work within the Transregio 10. The initial integrated calculations along the manufacturing process chain of partial frame structures showed the transferability of the introduced chaining method to further applications.

An overview of the application examples with an emphasis on the computational chaining approach is given in Table 6-1.

application example	manufacturing process chain	emphasis
sill board assembly	• deep drawing • cold rolling • (trimming) • laser beam welding	• clamping conditions • applicability of shell models
crash panel B-pillar assembly	• hot forming • deep drawing • (laser trimming) • resistance spot welding	• geometrical behaviour of the assembly • welding process operation sequence
composite profile frame structure	• extrusion moulding (cooling) • drilling • friction stir welding	• consideration of solid models • application for composite structures

Table 6-1: Overview of the frame assembly application examples for realising the virtual manufacturing chain

6.2 Welding assembly sill board

6.2.1 Description of the manufacturing chain

The virtual manufacturing process chain of a sill board is studied in the following. The frame structure assembly consists of two formed steel components, as illustrated in Figure 6-1: the web closing plate of the bake hardening steel 1.0396 (H 220 B) and the reinforcing U-profile of the dual phase steel 1.0941 (H 340 X or DP 600). The manufacturing chain involves the following steps:

- forming of the single sheet metal components by means of cold rolling (U-profile) and deep drawing (web plate);
- trimming of the web plate by means of shearing; and
- laser beam welding of the assembly in an integrated manufacturing step.

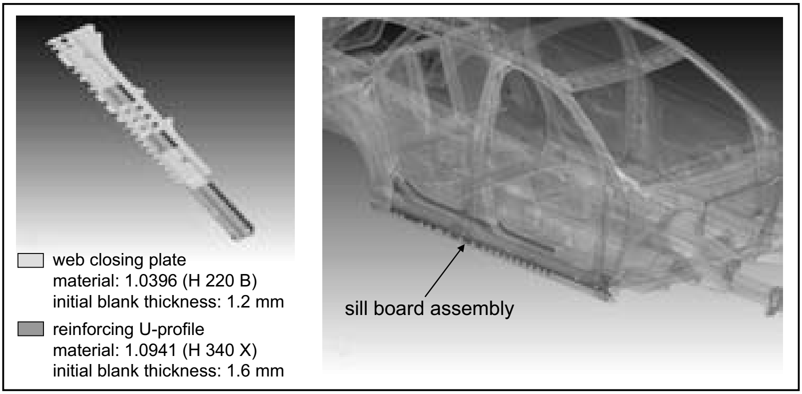

Figure 6-1: Sill board assembly consisting of a reinforcing U-profile and a web closing plate positioned in an automotive frame structure

6.2.2 Forming simulation results

In the first step, the forming simulation of the components involved is demonstrated. The cold rolling process of the U-profile was approximated with a deep drawing process by means of an elongated die. The transient character of the rolling process along the length of the sill board reinforcing part was, thus, neglected. Based on investigations the roll process generally provides very accurate components without strong spring-back effects in the length direction of the profiles. The spring-back effect of the side walls of the profile is avoided in real processes through over-bending of the profiles depending on the material strength (UBECO 2004). These effects were replicated in an approximating deep drawing simulation of the U-profile, so that the resulting shape of the U-profile after spring-back was very similar to the CAD construction of the part, indicating only negligible shape deviation. This simulation task was performed with the aid of the software AUTOFORM. Similarly, the forming simulation of the web plate by means of a deep drawing was performed in the FE-programme PAMSTAMP. After trimming and spring-back the final state was calculated showing no significant shape deviation compared to the CAD geometry. For this reason, the spring-back computation was accomplished in PAMSTAMP as well and it was not integrated in this example into the welding simulation, since the formed parts corresponded perfectly to the ideal shape provided by the CAD data.

The forming simulation of the two components provides the structural results of the parts after the forming process by considering a CAD-based geometry of the punch. The residual stresses after forming, trimming and spring-back simulation are shown in Figure 6-2. It can be seen that in areas where the deformation degree is high (i.e. in the middle chamfer of the U-profile), the residual stresses rise.

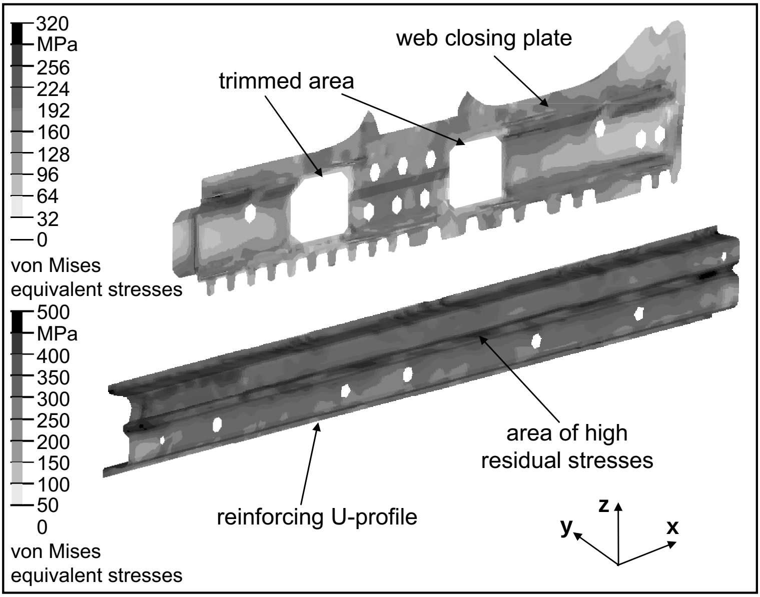

Figure 6-2: Computed residual stresses after forming, trimming and spring-back for the involved components of a sill board assembly as a basis for successive simulations

6.2.3 Simulation of welding distortion by multi-level analysis

The simulation of the welding distortion is based on the approach introduced in section 4.2 and on the chaining method described in Chapter 5. The available structural results after the simulation of the forming process (i.e. residual stresses, material thickness and effective plastic strains) were mapped onto the pre-defined mesh of the sill board assembly and converted with the aid of algorithms into an ASCII format, which is readable by the FE-programme SYSWELD. This mesh was based on the CAD geometry for the welding simulation and indicates a mesh refinement in the area of the seams, according to sub-section 4.2.2. The chaining of the forming simulation results into the welding simulation took place by means of a shell model, as introduced in Chapter 5.

The welding simulation of the sill board assembly was carried out in two stages: first the thermo-metallurgical simulation of the heat input of a laser beam welding process and the calculation of the phase transformation were performed based on the process parameters given in Table 4-2 and the corresponding macrograph of the seam cross section shown in Figure 4-7. A number of weld seams were realised by means of a tandem CO_2 laser beam aggregate heating parallel on both sides along the length of the assembly. Furthermore, the thermo-mechanical simulation of the welding process was performed based on the transient temperature field and phase transformation provided by the thermo-metallurgical simulation. Two different mechanical computations were accomplished: one without considering structural effects due to preliminary manufacturing processes and one considering the influence of structural effects after the simulation of forming. Hereby, the clamping condition generally has a considerable influence on the structural behaviour of parts. During the heat input (i.e. the welding process) the assembly components were held in a clamping device and were pre-bent according to Figure 4-12. This process stage is also described in the simulation, as illustrated in this figure. After about 25 s at the end of the welding process the assembly was removed from the clamping device and the distortion over time was measured.

Figure 6-3 shows the final welding distortion of the two components of the sill board assembly by considering the computed structural results after forming. The graph indicates the improvement of the transient computed welding distortion with respect to measurements in the defined position, for a model which includes structural results after forming, as compared to a non-chained model. As outlined in previous chapters, the interaction of the residual stresses after forming, together with the stresses due to pre-bending in the clamping device and the residual stresses in the seam area after welding, cause complex structural behaviour during welding. The high degree of non-linear interaction of the induced stresses along the manufacturing process chain of the sill board assembly can be described by means of simulation methods. The consideration of structural effects along the manufacturing chain in the simulation provides an improvement (compared with sole welding simulation) concerning the prediction of the final distortion of the frame assembly from 42% down to only 9% deviation.

7 Summary and Outlook

This thesis highlights the current potential of computer-aided and simulation methods for describing the structural behaviour of semi-finished frame products within the manufacturing process chain. Certain solutions based on computational methods were proposed and enhanced in order to support the manufacturing chain of complete frame assemblies. The virtual chain was developed on the basis of the simulation of the welding heat effects, as welding processes represent a central element of the manufacturing chain. The main focus was on the applicability and the adoption of these kinds of methods for supporting manufacturing tasks in the transport industry, in order to improve product quality and minimise expenses.

Chapter 1 outlined the significance of simulation methods in supporting manufacturing tasks. Emphasis was placed on developing an integrative method of considering individual manufacturing tasks in a holistic computational manufacturing process chain.

Chapter 2 presented the main theories and computation fundamentals for modelling and simulation in manufacturing. Forming, metal cutting and welding processes were discussed. Numerical simulation on the basis of the Finite-Element-Method (FEM) provided a suitable tool to model manufacturing processes with the main focus on the structural effects of treated components.

Based on previous works in the field of simulation of manufacturing processes, the current state of research was presented and evaluated in Chapter 3. The need for further research work and the focus of this thesis was outlined. Particular consideration was dedicated to realising an integrated virtual manufacturing chain method by enhancing existing computer-aided systems. The solution requirements are that the developed method is system-independent and flexibly applicable concerning the used FE-programmes, the used data formats and the regarded manufacturing processes and, thus, offers operator convenience.

With the welding process as the central element of the manufacturing chain of frame structures, Chapter 4 analysed and enhanced different models with regard to the heat and structural effects during welding. Emphasis was placed on the categorisation of the welding models in a multi-stage simulation system depending on the degree of complexity of the considered influencing phenomena. Different models, which allow the description of the complex physical effects

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Appendix

Appendix A: Applied programmes

Software tool	Area of application	Producer
SYSWELD	Simulation of structural heat effects of welding and heat treatment; FEM-software	Engineering Systems International ESI GmbH
MSC. MARC	Simulation of structural effects of manufacturing tasks; FEM-code	MSC.Software GmbH
PAMSTAMP	Forming simulation and mapping functions; FEM-software	Engineering Systems International ESI GmbH
AUTOFORM	Forming simulation; FEM-software	AutoForm Engineering GmbH
LS-DYNA	Simulation of hot forming; FEM-code	DYNAmore GmbH CAD-FEM GmbH
PATRAN	FEM-meshing tool	MSC.Software GmbH
HYPERMESH	FEM-meshing tool	ALTAIR Engineering GmbH
DATOR	Mapping tool	INPRO GmbH
ATOS	Optical system for digitalisation and analysis of surfaces	GOM mbH
SIL (Systus Interface Language)	Implementation of sub-programmes for the realisation of simulation chaining	Engineering Systems International ESI GmbH
perl (programming language)	Implementation of sub-programmes for the realisation of simulation chaining	The Perl Foundation

```
#
#Conversion routine for stress tensor from GPa to MPa
#
open IN, $ARGV[0] or die "\n\tNo input file specified!\n" ;
my @fileContent = <IN> or die ;
close IN or die ;
#
my $rowIdx = 0 ;
my $expValue ;
foreach ( @file Content ) {
  $rowIdx += 1 ;
  last if /INITIAL_STRESS_SHELL/ ;
}
#
$rowIdx += 1;
while ( 1 ) {
  foreach ( 1 .. 5 ) {
    foreach my $colOffset ( 18, 28, 38, 48, 58, 68 ) {
      $expValue = substr( $file Content [ $rowIdx ], $colOffset, 2 ) ;
      substr( $fileContent[ $rowIdx ], $colOffset, 2 ) =
                        sprintf( "%+2d", $expValue + 3 ) ;
    }
    $rowIdx += 1 ;
  }
  $rowIdx += 1 ;
  last if $rowIdx > $#fileContent -1 ;
}
#
open OUT, ">$ARGV[1]" or die "\n\tNo output file created!\n" ;
print OUT @fileContent or die ;
close OUT or die ;
```

Perl-routine for the conversion of the unit of stress tensor from GPa to MPa in order to achieve consistency of units within the welding simulation

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