Newest developments in metal forming process simulations to meet future requirements

Dr.-Ing Hendrik Schafstall; Dipl.-Ing. Michael Wohlmuth; Dr.-Ing. Christian Barth;
Dr.-Ing. Gabriel Barton
Simufact Engineering GmbH, Hamburg

Abstract

Process simulations have become a standard tool in design and development departments which is used more than ever. In certain applications there is no parts anymore which have not been simulated prior being manufactured. Initially, only the material flow was investigated using simplified process models. Today, the range of application of simulation tools covers increasingly tool loads and their impact on the metal forming process itself requiring a realistic model of kinematic process parameters. The effects of tool stiffness are considered rudimentary. The aim is a high precision of predictions and high quality of the computed results, both require for effective solvers and a precise representation of the underlying physics. In addition, increasingly adaptive and partially self-organising optimisation strategies are used, which for the most part depend on customer specific modifications. These are only possible if the used software is flexible and provides open interfaces. In addition, a close cooperation between the user and the software developer is essential.

The process simulation is only one, but early, step in the life-cycle of a part. Manufacturers increasingly analyse entire process chains as the production of the primary material, its further processing, manufacturing of individual parts and their joining, as well as intermediate and final heat treatment processes. The goal is the holistic layout of processes considering the characteristic properties and requirements of individual parts. Metal forming simulations and structural analysis grow together. Because of the core technologies MSC.Marc (FEM) and MSC.Dytran (FVM) used in Simufact.forming versatile possibilities arise to meet future requirements of holistic simulations. Another requirement is the user-friendly coupling of existing third party solutions for optimal benefit of the user. This paper presents and discusses some approaches for integrated simulation of process chains and their realistic representations.

1 Introduction

Both, the precision of predictions of part properties as well as of entire assemblies and the virtual process design of new and the optimisation of existing metal forming processes gain more and more relevance. A high accuracy of the models and the computed results is fundamental and taken for granted.

Particular interest is expressed to the modelling of the process determining machine parameters and the properties and formability determining material data of new and more complex materials and material composites. Furthermore, "intelligent" closed loop control algorithms are integrated in simulation software, to accurately represent the control algorithms of metal forming machines and to more precisely represent the real processes. This allows to exploit further optimisation potential.

One of the strengths of simulations is, next to the look "into the processes", the possibility to try out ideas and validate concepts, to examine a large number of variants and to carry out sensitivity studies. For this purpose Simufact.forming provides special automatic optimisation algorithms, which organise a large number of variants, carry out the required simulations and evaluate them and finally describe the results. This considerably unburdens the user.

Another trend in the simulation is the consideration of the manufacturing history in subsequent manufacturing processes targeting the precise prediction on the properties of individual parts and assemblies of components. These results are increasingly required for the subsequent structural and fatigue simulations. Furthermore, the simulation allows for a systematic adjustment of component properties in the interdisciplinary concurrence of individual manufacturing steps and activates further idle time and cost potentials.

A challenge for the simulation of entire process chains and their individual aspects is the usability of the applied programs, which must be user-friendly, praxis-oriented and interpretable. Here, some developments of Simufact hereto will be presented and discussed. These developments are carried out with close cooperation with customers and research organisations from different disciplines. The development steps and the potential for further developments are still large and can be efficiently carried out by Simufact. This is due to the fact, that the Simufact-solver are based upon the "general purpose" solvers MSC.Marc and MSC.Dytran, which next to Abaqus and Ansys belong to the most universal and most powerful solvers worldwide. This allows to couple different disciplines at the highest technical level for the simulation of high quality results. Furthermore, a large number of material models (fully elastic-plastic, isotropic, anisotropic, kinematic hardening, Bauschinger effect, etc.), powerful contact algorithms with friction models, heat conduction, dynamic effects, complex kinematics of the tools (load-controlled or revolving, spring-loaded) and rigid-body-mode for the workpiece are available. Furthermore, the program is open designed allowing for fast adaptation to customer requirements and quick implementation of new functionalities. These are realised user-friendly and praxis-oriented. With this presented solution future requirements on simulations can be delivered customer-oriented and promptly to the different departments at the users.

2 Process chain

The term "process chain" is being used in different fields, from business processes to factory layout. Depending on the application, process chains are further subdivided and viewed at individually for individual segments. Here, the focus is placed on process chain analysis of selected metal fuming processes and the current developments carried out by Simufact are presented. The modelling of process chains for material production is not a topic of this paper.

The aim of a holistic modelling approach is the combination of subsequent manufacturing steps to all-over include part-properties and their development to the point of the finished product or the final assembly of parts. The complexity of these processes cannot be any more efficiently handled without simulation techniques. The industrial competition forces the enterprises to develop new products continuously faster until the start of production leaving less time for iterative trial and error experiments, which often result in expensive corrections, if the process window is not large enough. An example is short tool live, which can handicap the start of mass production, even if the process is principally manufacturable. Also, alterations of material properties or the production conditions, etc. result in a disrupted process. The process chain examination shall increase security and reliability and disclose possible serious disruptions.
Furthermore, more knowledge of the part properties of the final product are generated to indicate possible optimisation and improvement possibilities .
The following diagram exemplary shows a process chain, which can be arbitrarily extended or shortened. The simulated excerpt of the process chain is adjusted to the required analysis results.

Here, several parts are investigated, which are assembled to a finished product e.g. by mechanical or thermal joining. The properties of the assembly subjected to external loads will be analysed.
The examination of the history of the part allows for a deeper process understanding and a more specific adjustment of the final product, because it allows to specifically adjust individual process steps while still maintaining the overview of the entire process.

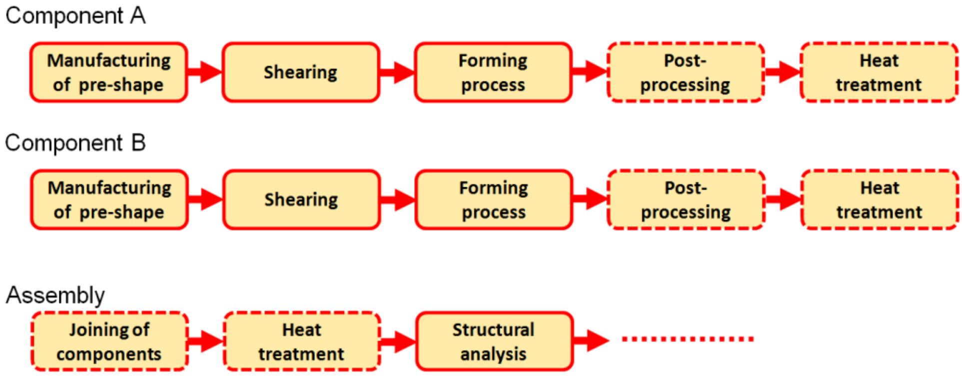

Figure 1: Exemplary depiction of a process chain

The philosophy of Simufact is to connect the best technologies available. This is carried out by several means. Either the methods are directly implemented to the software or interfaces or external modules are provided. For the examination of entire process chains different approaches are applied which will be demonstrated in the following Chapters exemplary on several parts.

2.1 Forging

A typical process chain of hot metal forming will be studied here.

Figure 2: Exemplary depiction of a forging process chain

Shearing

The shearing process is simulated in one step, also allowing to use a separate tool to determine the shearing zone, which cross-section is used for the shearing contour. The shearing process is therefore divided into a forming step and a subsequent forced rupture. This sequence is simulated in one process.

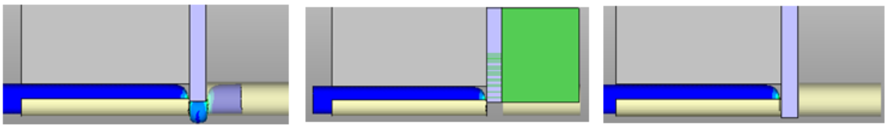

Figure 3: Continuous shearing process with forming phase and forced rupture

Inductive Heating

The inductive heating an additional program provided by ABP Induction Systems GmbH is used. Therein the temperature field is simulated, which is imported as an initial condition to simufact forming with an interface.

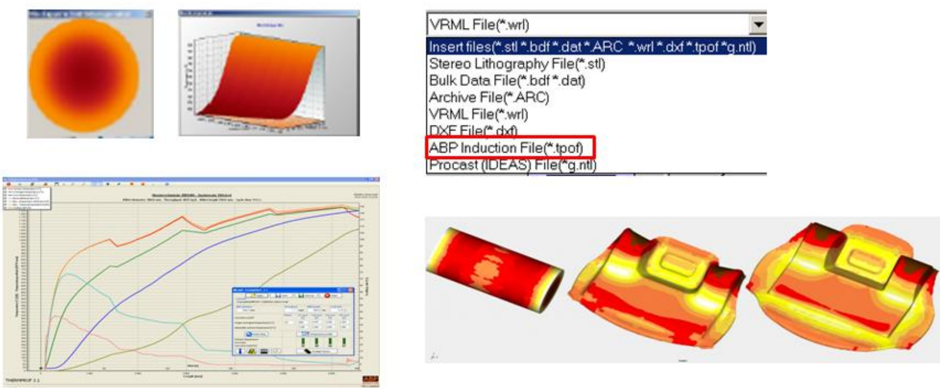

Figure 4: Calculation of the inductive heating with Thermprof and transfer of the temperature field to Simfact.forming

Forming process

The forming process is simulated in Simufact.forming based on the calculated temperature field. Microstructure simulations for the determination of grain sizes considering dynamic and static recrystallisation can be carried out. This requires a precise process control to precisely describe the temperature-time development. Furthermore, the strain must be exactly simulated, since it is the determining factor for microstructure models. Different microstructure models specific to the material and forming process can be chosen from.

Trimming

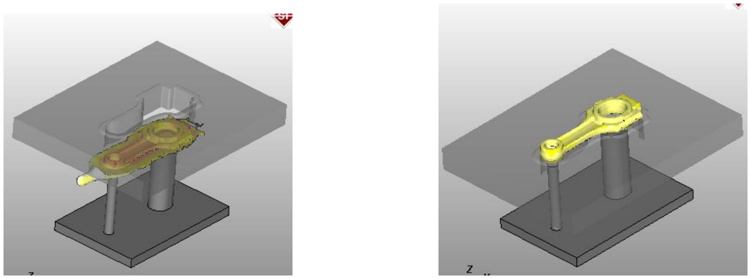

Figure 5: Continuous trimming process shown on the example of a piston rod with warpage simulation using elasto-plastic material properties

Following the forming process the part is trimmed and eventually cooled to room temperature. Often, this results in warpage, which requires rectification work.

Heat treatment

Next, the part is subject to heat treatment to adjust the properties. Several approaches are implemented, which partially depend on different modules. As of the next release, the entire process starting with the forming simulation will be modelled in one pass to calculate the properties of the finished product. During the development, special focus was placed on usability allowing to be used by uninitiated. Up to seven steps can be considered (Fig. 6):

I: Heating following a temperature-time function simulating the resulting temperature field and grain growth

II: Holding phase calculating the austenitisation controlled by time and temperature

III:. Cooling phase with different media, both locally and timewise distributed, calculating the transformation heat, volume changes during the phase transition (Austenite to Ferrite, Austenite to Martensite, etc.) and the plastified fracture. This allows the accurate prediction of distortions and the residual stresses.

IV: Pause time, calculating eventual changes of the temperature field.

V-VII: following that, the annealing can be directly calculated.

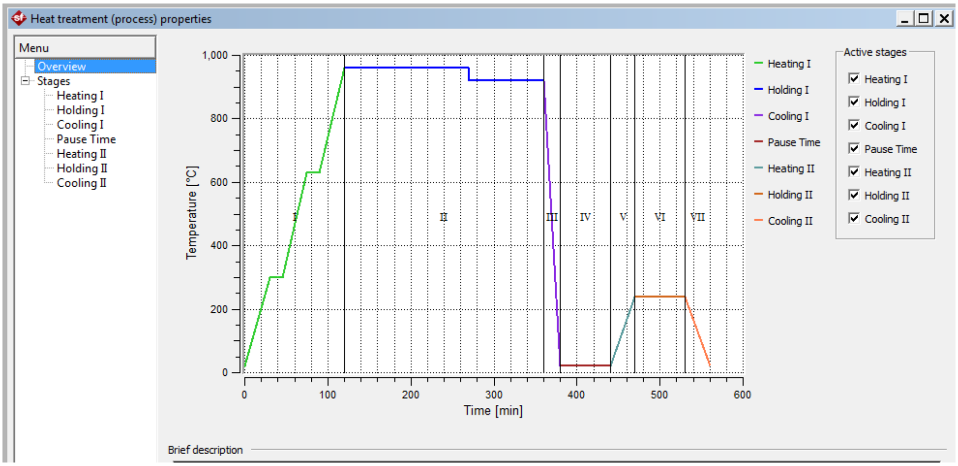

Figure 6: Input of the heat treatment stages in Simufact.forming.

The result of the calculation can be used in subsequent simulations as an initial condition (residual stresses, phases, etc.), e.g. to simulate mechanical or thermal joining and to carry out further numerical simulations (durability analysis, static and dynamic loading, etc.).

For the majority of steels the mechanical and thermo-physical material properties as well as the flow curves are available for their individual phases based on the chemical composition. An averaging is carried out dependent on the phase proportions. Additionally, the isothermal and continuous TTT-diagrams and the yield stress is available. All material properties are provided and visualised by a user-friendly material module and can be applied for all simufact programs (forming, heat treatment, welding). In a process chain simulation it is beneficial to use a consistent material data base.

2.2 Open die forging

This example of a open die forging process will demonstrate further aspects of process chain modelling.

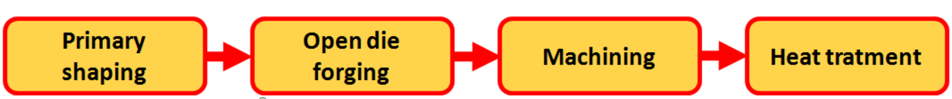

Figure 7: Exemplary depiction of a open die forging process chain

Primary shaping

Excellent and established systems for the simulation of primary shaping, especially casting are readily available. Hence, these models are not integrated in simufact.forming but linked to with interfaces. In the first instance an interface to ProCast was developed, further interfaces are being developed. The simulated geometry of the ingot and its simulated properties, among others, e.g. the distribution of blow holes is imported. The closing of the blow holes is simulated during the open die forging process.

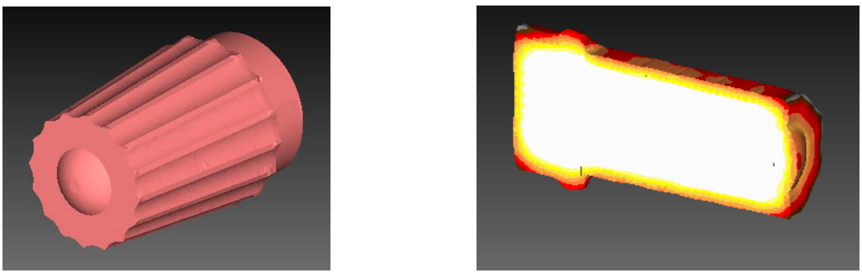

Figure 8: Geometry imported form ProCast (left) and the temperature field at the end of the open die forging process (right)

Open die forging

The sequence of individual forming steps in open die forging is very complex. Simufact.forming has a kinematics module, which was developed for a large number of different incremental forming processes, which allows an automatic process simulation of several passes and multiple heats. The open die forging process is simulated automatically appropriate to the forging schedule. This open loop control allows an adaptive optimisation, since the computed conditions (deformation degree, force, porosity, damage, texture, temperature) are available after each forming step as well as the geometry. From these values, the subsequent forming step can be derived. The interface can be adjusted to the customer's requirements.

This kinematics-module is available for ring rolling, shell forging and radial forging.

Machining

Next, the final part geometry is computed containing the simulated properties, which can be used for the following heat treatment process. The sequence can be carried out in any order. With this approach the machined volume is removed and the resulting distortion and changes in the residual stresses computed.

Heat treatment

The heat treatment is simulated in Simufact.forming defining the final properties of the finished part (see above).

2.3 Sheet metal forming / Thick sheet metal forming

Figure 9: Exemplary depiction of a sheet metal forming process chain

The new possibilities and potentials of (thick) sheet metal forming simulations shall be presented here, which are also applicable to cold bulk metal forming processes and to a combination of these. A typical sheet metal forming process is depicted in Fig. 10:

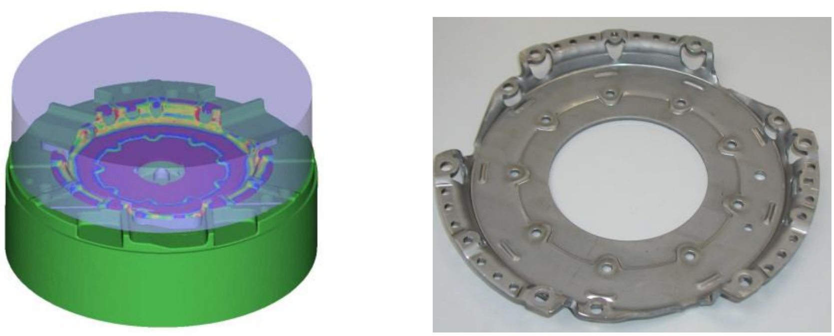

Figure 10: Typical sheet metal forming simulation (left), finished part (right) (courtesy of ZF-Sachs-AG)

Production of the pre-shape

Depending on the impact on the entire process chain the production of the pre-shape can be considered to a certain extent. Thereto e.g. the rolling process for the manufacturing of the steel blank of in the case of cold metal forming the distortion of the wire can be simulated. Typically however, an isotropic material is assumed, but if required an anisotropic behaviour can be considered. This requires additional material properties and the knowledge of the rolling direction of the blank.

Shearing

If the shearing process or the precision-blanking has a considerable impact on the subsequent forming steps due to the impact on the material geometry and material distribution or a local strain hardening, it can be simulated in the run-up of the main process simulation.

This shearing process is divided in a forming and a forced rupture. As of now, there is no universally valid fracture models, which can be blindly applied to predict the point in time and the direction of the rupture. An adequate method is to at first model the metal forming and then after a certain predefined stroke to split the material. The ratio between the forming stroke and the rupture has to be measured on the real part and is normally between 1/3 - 2/3 of the thickness. Typically, as of now fine-blanking processes are simulated separately and optimised, but not taken as the basis for subsequent forming stages. Multiple fine-blanking operations can be continuously modelled within one process using a number of different and arbitrarily activated trimming tools.

Forming process

The forming process can be modelled as a whole including all kinematic characteristics, e.g. the stroke and the back stroke of the press, and the activation of additional actuated tools. To further increase the accuracy springs parameterised with tabular defined forces of stiffness can be added. These springs can be arbitrarily activated- and deactivated in time. This allows for an very realistic representation of the reality and accurate simulation results of the residual stresses, spring-back and thickness distribution.

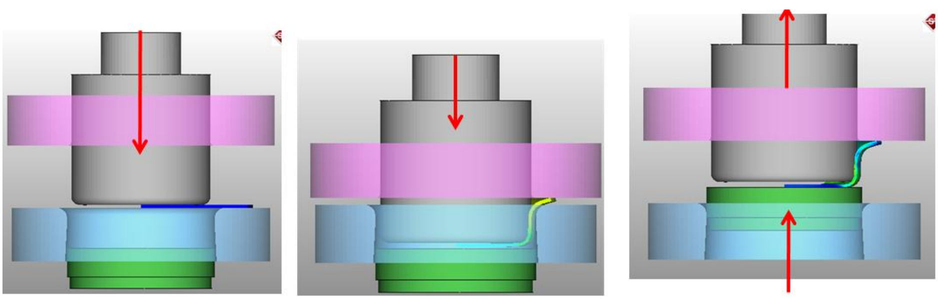

Figure 11: Integrated forming operation with stroke and back stroke and an additional movement of the counter punch during the back stroke

Another example is shown here for a connected multiple-stage part. The simulated results are shown after tree forming steps in Fig. 13.

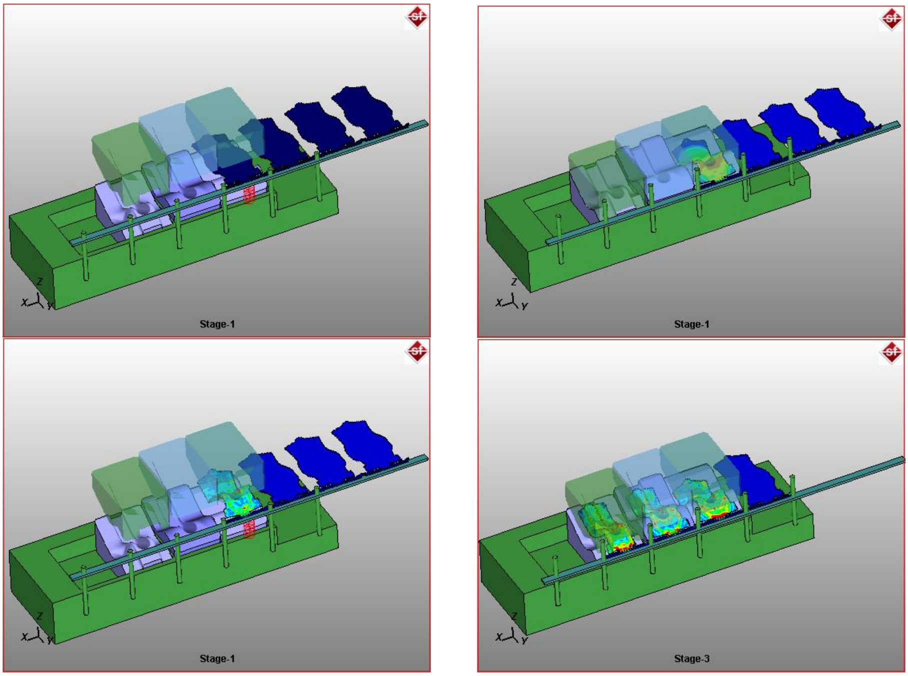

Fig 12: Connected multiple-stage with forward and backward stroke and automatic transfer

Each step is modelled as an individual process for the forward and the backward stroke. Following that, the blank is translated to the next forming step and the next stroke follows. Coupled with the stage-control functionality, this process chain can be simulated in one run without user interaction.

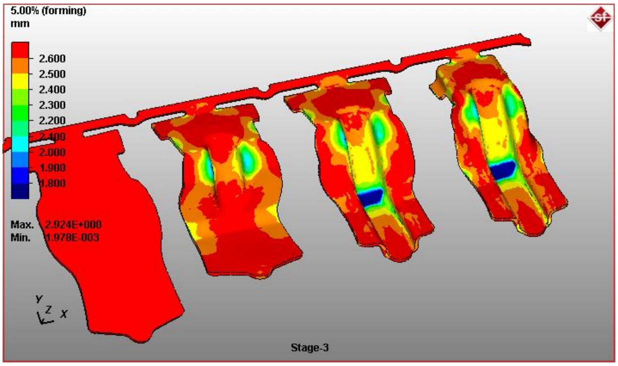

Fig. 13: Simulated sheet thickness after the 3. stroke of a connected multiple-stage part

3 Description of the process chain: Forming of an typical automotive part with subsequent thermal joining

A large number of parts is joined mechanically or thermally after being formed. Mechanical joining is part of metal forming simulations since several years. Thermal joining is welding, which results in partially altered properties. Further distortion is added, which is superimposed to the residual stresses of the leading process steps. Welding simulations are now carried out in separate departments specialised in fundamental analysis. Their application was always time consuming and complex.

Due to the importance of their results, welding simulations become a larger focus in the manufacturing industry. For this reason, Simufact was assigned 6 years ago with the development of an new simulation program focussing on the requirements of the customers by the research-group welding simulation of the German automotive industry.

This program has been released and is being marketed alongside with Simufact.forming.

It is user-friendly and incorporates the latest developments into a modern concept. Now it is being merged with simufact.forming to allow through process simulations of entire manufacturing process chains.

Besides the prediction of the properties of the assembly, the welding simulation is applied to determine the best sequence of welding steps, to determine the introduced heat and to determine suitable clamps to minimize the distortion.

A key are the clamps, which on one hand hold the individual parts together and shall compensate eventually during the preceding manufacturing steps introduced distortions and shall prevent distortions of the welded part. The thermal impact can release further residual stresses which may lead to increased distortions. Today, mainly the (constructive) sheet thickness is optimised and the heat sources adjusted. The forming steps cause wall thinning and wall thickening. Accordingly, the heat sources and the robot kinematic have to be adjusted to the real geometry. A holistic approach allows to maintain narrower tolerances and results in increased process stability and better product properties.

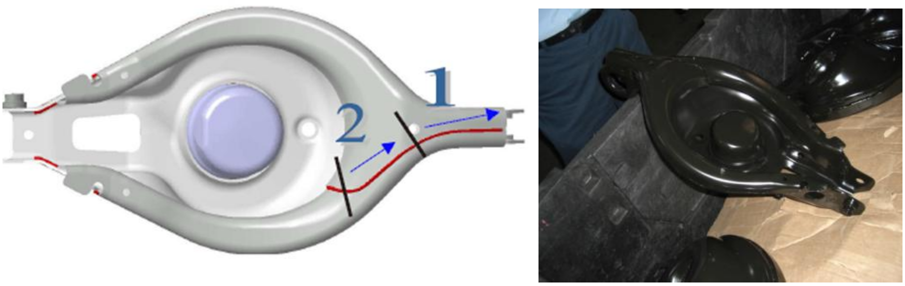

Figure 14: Welded assembly of sheet metal formed parts in the automotive industry

The metal forming simulation of the parts to be joined is carried out with Simufact.forming. Following that, the components are welded in Simufact.welding. The example shown here, originates from a project of the Mississippi State University, carried out in cooperation with Prof. Keiichi Motoyama. The assembly is shown in the following Figures as a CAD-file and the real component. The process chain is consists of the following steps:

Process chain

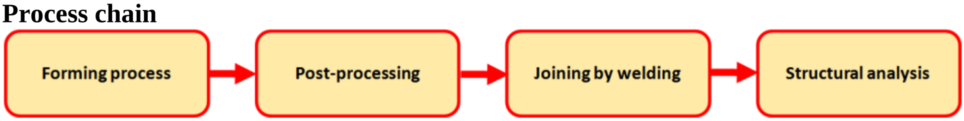

Figure 15: Schematic representation of a process chain forming and welding

Here, only two selected parts will be described in further detail focussing on the description of the procedure.

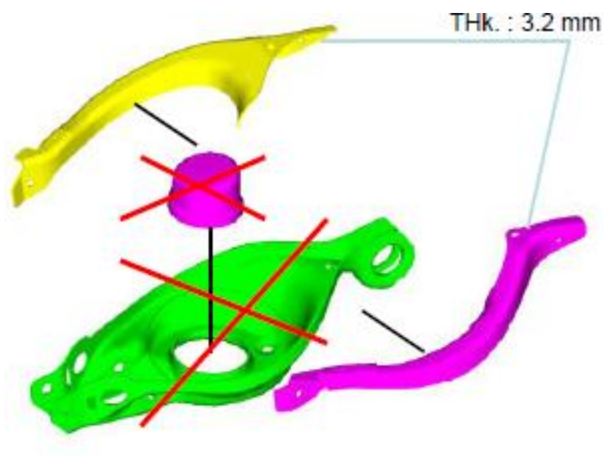

Figure 16: Examined components

Metal forming process and post-processing

The metal forming process of components to be welded is simulated with a multiple-step composite tool. The geometry of the initial blank is given by its CAD-geometry with a constant sheet thickness. After the forming step including the spring-back the part is trimmed in a following simulation step to its final geometry including all required cut-outs. The components are now available in their final geometry and simulated sheet thickness distribution and all other properties, e.g. strain hardening and residual stresses to name the most important.

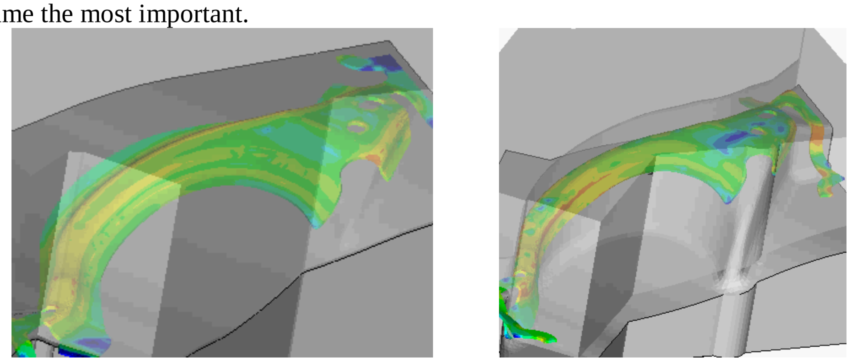

Fig 17: Forming process of a sheet component prior the post-processing in 2 steps.

Joining by welding

Next, the geometries are imported in Simufact.welding and the clamps and all relevant process properties assigned. Following this, the simulation of the welding process of the components is carried out. Following the welding simulation, the assembly is cooled and the clamps released according to their timing sequence.

The simulated distortion at the end of the welding process is shown in Figure 19.

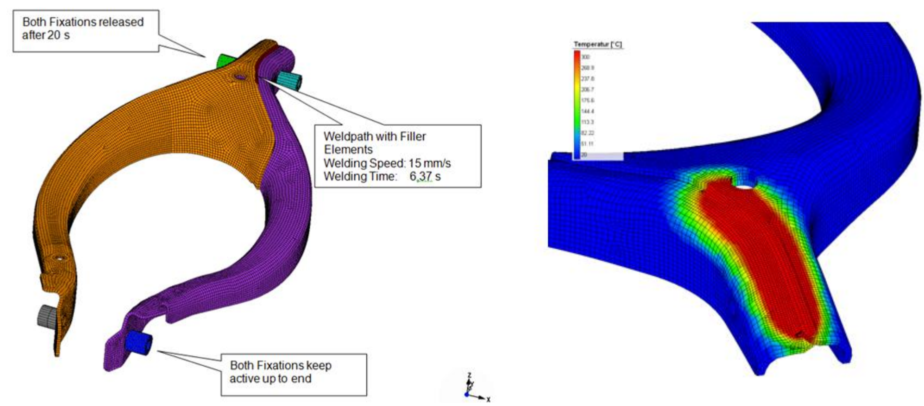

Figure 18: Simulation model of the welding process (left), simulated temperature distribution along the first welding path.

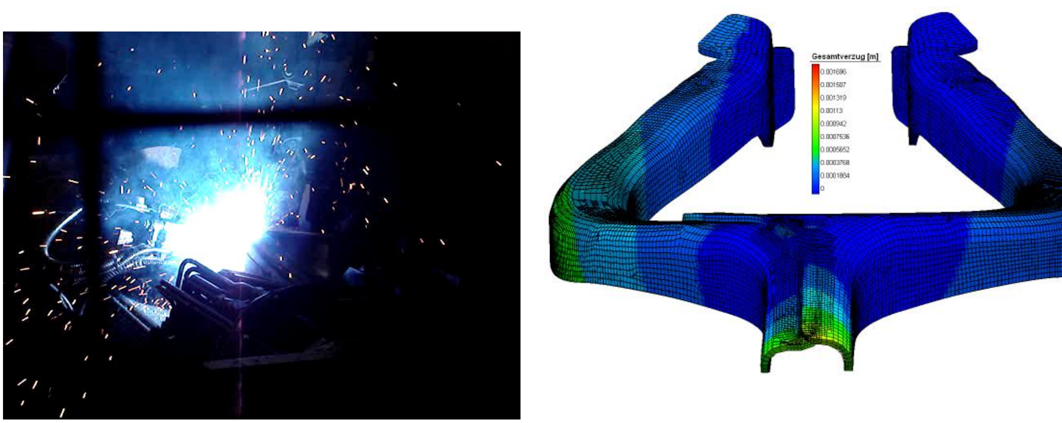

Figure 19: Real welding process (left) and simulated integral distortion at the end of the welding process of a typical component(right)

Heat treatment

Depending on the real process chain, the welding simulation can be followed by a heat treatment simulation in Simufact.forming, again based on the component properties of the preceding thermal joining step.

Structural analysis

In principle, also a structural analysis can be carried out with Simufact.forming. Further possibilities will be added in a user-friendly manner in the future. Also, universal interfaces to other programs specialised in structural analysis will be provided, allowing to consider the properties resulting from the manufacturing history.

3.1 Consideration of tools and machines

Increasingly the coupling of tools and the work pieces as well as the coupling of machines - tools - workpiece are more intensively studied. This can be achieved by several means. The stiffness of the machines can be represented by on-linear springs.

Coupled simulations

The processes, in which the elasticity of the tool has an direct impact on the material properties and the geometry, are increasingly simulated fully-coupled with elastic tools. The increased computing time can be partially compensated with DDM-parallelisation. The thickness distribution, the final geometry after spring-back and the residual stress distribution can be very accurately simulated and the individual components of the tools can be well-directed optimised.

Additionally, reinforcements can be applied to optimise the initial pre-stresses. A complex tool assembly representative for a cold forming process is shown in Fig. 20. In the third forming step segmented forming tools are applied.

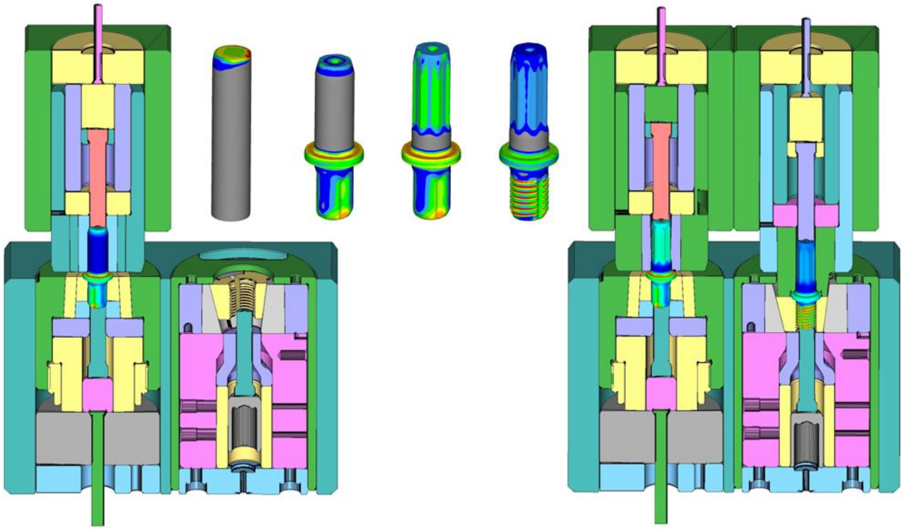

Figure 20: Entire tool assembly of a tool concept for thread embossing in a two die three stroke press

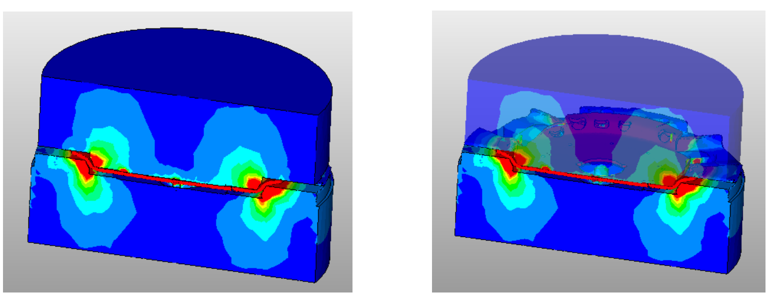

Figure 21: Fully-coupled simulation of a sheet metal forming process with elastic tools at 70% of the forming process.

Decoupled simulation

For many application it is sufficient to analyse the tool loads in an decoupled simulation. Predictions about the die wear can be directly derived from the forming simulation. All tool movements and rotations, also for spring-loaded tools are transferred from the forming simulation and allow for a tool analysis from the first to the last forming step. By these means, a complex tool assembly can be simulated in a decoupled analysis. This approach also allows to split tools and to optimise reinforcements, without being required to repeat the forming simulation for each modification.

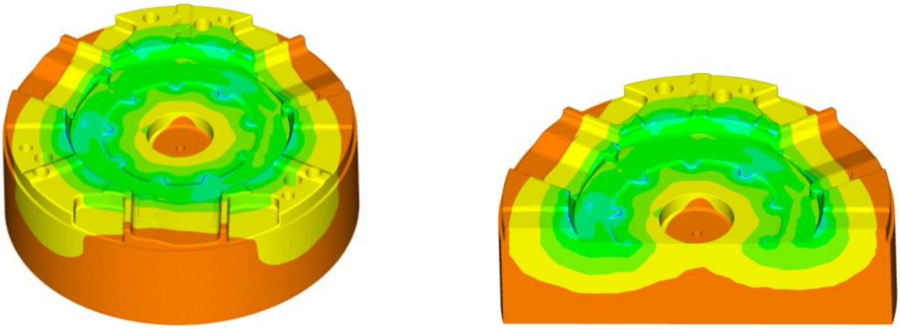

Figure 22: Tool loads in the lower die analysed in a decoupled simulation at 100% tool loads..

4 Summary

The holistic analysis of an integrated simulation of process chains is of ever growing interest, considering the process history of a component until it is assembled to a complex assembly. With the product family Simufact.forming and Simufact.welding, as well as the implementation of interfaces to other simulation programs the user has an extremely powerful and trendsetting concept at his disposal. Simufact continuously develops the software in tight cooperation with its customers based on their suggestions, ensuring that future requirements to the software are in accordance with customer requirements and provide a competitive advantage. Because of the basis technologies of MSC.Marc and MSC.Dytran manifold possibilities for future advancements in Simufact can be provided promptly. The open concept allows a fast realisation and the integration of further technologies.

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