From cast ingots to the heat treated part - automated simulation of the process chain

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Introduction

Both the international competition and the globally changing economic and environmental conditions lead progressively to rethinking in the field of industrial manufacturing. Future product developments and the development of the related manufacturing processes will be driven by resource-effectiveness and component properties enhancing manufacturing process chains.
As hitherto, many manufacturing process steps have been individually analysed and optimised without considering their interaction with subsequent steps. By targeted adjustments significant potentials in respect to energy consumption and manufacturing effort can be activated. This is in particular the case for process chains with high energy requirement, e.g. incremental forming processes like open die forging, shell forging and ring rolling. Component and product properties can be set and adjusted by the manufacturing process already an early stage.
The knowledge of the respective physical correlation and about their targeted manipulation becomes ever more important, in fact at an interdisciplinary level. A modern tool to exemplify and visualize these interactions is numerical process simulation. By means of process simulation feasibility studies as well as process optimisations and sensibility studies can be carried out and herewith a deeper process understanding be gained.
Simulating tools are already applied in the different disciplines, but without utilising the knowledge for subsequent manufacturing process chains. Often over and over again homogeneous material properties are assumed and the impact of previous steps is neglected. In this paper some approaches are presented showing how future challenges of incremental forming processes can be met by the help of numerical simulations.

From the casting to the final part

Figure 1 shows a typical process chain for the manufacturing of a metal component. Starting form a casted billet it is forged in several heats into a pre-shape. The pre shape is machined and heat treated. A final machining makes the part ready for the use under operating loads.

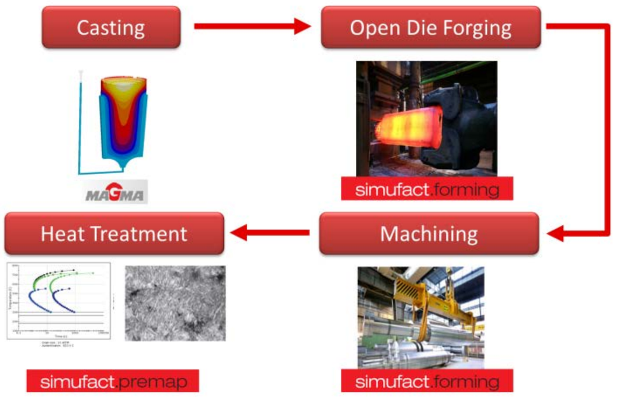

Figure 1: Process chain from the cast Ingot to the final heat treated product

During the individual process steps the microstructure is repeatedly impacted and modified by different mechanisms. During the casting process the initial microstructure is formed, which is not homogeneous. During the subsequent process steps plastic deformation, temperature changes and gradients of the chemical composition lead to the mechanisms shown in Figure 2. These mechanisms are considerably affected by the initial microstructure. Thus the local composition at the beginning of the open die forging process needs to be considered in the simulation.

	Recrystallization	Phase-transformation	Diffusion
Initiator	Plastic deformation	Temperature change	Composition gradient
Target values	Recrystallized volume fraction Grain size distribution Flowstress (change) Tensile strength	Phase distribution Hardness Residual stresses Flowstress change	Concentration of alloying elements Hardness Flowstress change

Figure 2: Most important physical effects for the microstructure during forming and heat treatment

An example for this shows Terhaar et. al. (2010) presenting cogging simulations in which the initial microstructure defined by the solidification structure of the ingot leads to anisotropic plastic yield due to the crystal orientations and to locally different resistance to damage due to segregation. Combining both, the occurrence of damages in the core of ingots made of alloy 718 can be explained. Figure 3 shows the result of upset specimens based on the solidification structure by using an adaptive material model. Therefore it is important to be able to consider the cast microstructure as the initial condition for the metal forming simulation.

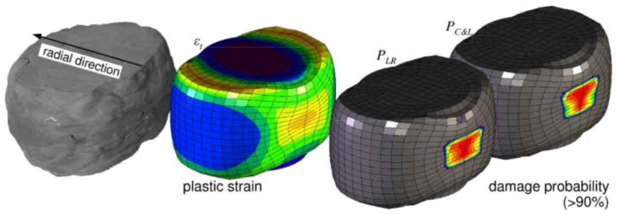

Figure 3 Comparison of real and simulated behaviour with the adapted material model.

Process simulation

For the individual target values of the different manufacturing process steps there are varieties of different process models and simulation software systems. The casting of the Ingot, including the solidification process can be simulated for example with casting simulation software as MagmaSoft. Target of this simulation is to optimise the casting process and to predict the microstructure of the casted billet.

Among others the main result values interesting for the subsequent process steps are:

- Macroscopic blowholes (Figure 4)
- Microscopic blowholes (Figure 5 & 6)
- Macrosegregations
- Distribution of alloying elements (Figure 7)

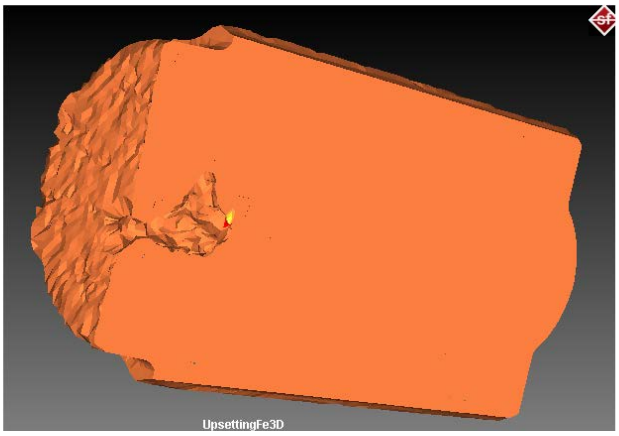

Figure 4: Macroscopic blowholes from casting simulation as initial geometry for cogging simulation in Simufact.forming based on a hexahedral mesh.

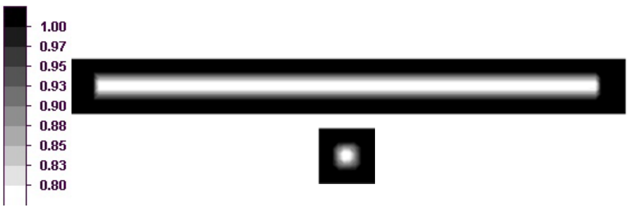

Figure 5. Initial relative density, cross section lengthwise (above) and crosswise (below)

Figure 6: Relative density after the cogging process, cross section lengthwise (above) and crosswise (below)

For the consideration of the casted condition as the initial condition for the simulation of the subsequent metal forming and heat treatment steps an interface was developed with an industrial partner. This interface transfers all relevant result values. The results are imported and mapped to the mesh in simufact.forming.

Figure 7 illustrates this on the example of the local contents of the alloying elements Carbon and Chromium. These local contents are traced during the entire process chain simulation and modified according to the physical properties (deformation, temperature and diffusion). This has in turn an effect on the local material properties. More physical models have been integrated during the project, in order to calculate the properties of the product during the manufacturing process as well as of the finished product. This was carried out in close cooperation with nameable research institutes. The simulation provides the initial parameters which linked and interacting with the integrated material models are carried along the entire process chain simulation.

Die microscopic blowholes have been initially computed with MagmaSoft based on the Nijama criterion and are converted to the relative density for the subsequent simulation. The simulated partial densification of the microscopic blowholes is shown exemplary in Fig. 5 and 6.

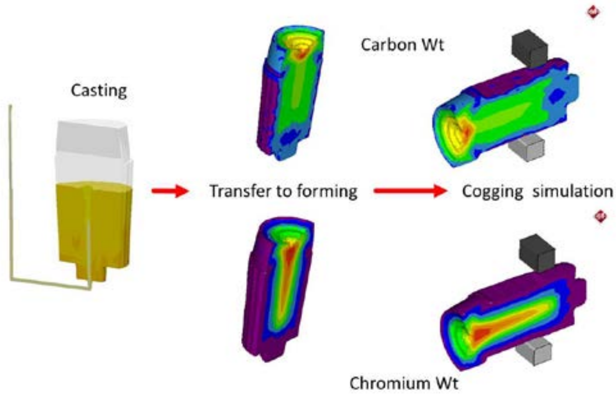

Figure 7: Content of alloying elements

Fig. 8 shows the simulated temperature distribution (right) and the plastic strain during the open die forging in the first heat. It shows clearly the areas with different temperatures, which in turn superimpose segregations and lead to locally different conditions, which are also partially visible at the end of the workpiece.

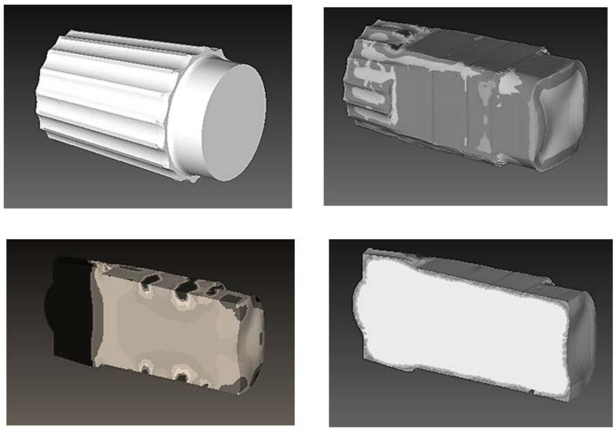

Figure 8: Temperature distribution (right) and plastic Deformation (below, left) at the end of stage 1 for the first heat

Software engineering realisation

The different material models and the incremental external loads result in ever changing conditions, so that a new equilibrium must be found in each time step. This is the more complex, the more the microstructure changes, e.g. if the lattice shearing occurs. This requires a powerful numerical solver and the possibility to consider all relevant aspects. Simufact.forming is in this respect by far uses the most advanced solver on the market. It economically allows for very precise and realistic computations. The simulations are carried out with hexahedral-elements, which provide a very precise computation of the stress and straining state. This results in precise predictions of the final component properties. Figure 6 shows the interdependencies and the different submodels implemented in Simufact.forming.

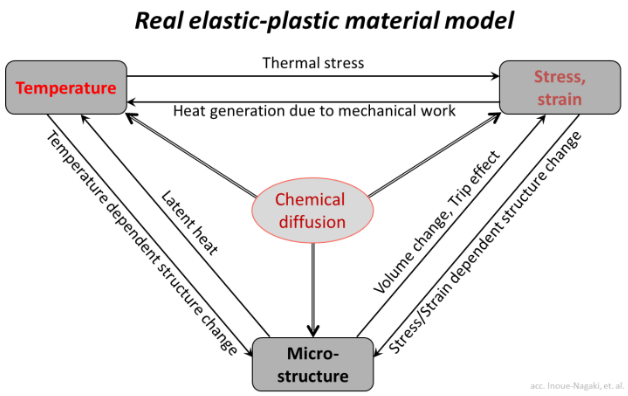

Figure 9: Interdependencies and submodels for the material model

This is a core functionality and a basic necessity, because all models are meritless if no precise calculations are possible. Consequently, a real elasto-plastic material model is used to accurately compute the residual stresses. They are computed during all process steps until the final part, where they can be used as auxiliary stresses to bear the loads.

A new flexible data structure for the handling of material data required for these computations was created and implemented in Simufact.forming. This material data base considers the chemical composition and provides an infrastructure for phase dependent material properties. Based on the phase composition at the individual integration points microstructure dependent material properties can be computed and used for the calculation of the stress state.

Next to the internal material data infrastructure an open and modular external material management tool was developed which centrally files and visualises all required material parameters (Fig. 10). New models can easily be added and coupled with the simulation. It stores all material properties required for the forming simulation as well as the parameters for the different microstructure and phase transformation models. The full integration to Simufact.forming allows the computation of the forming process at the same time with phase transformations and the microstructure development (see also Figure 6). These programs have been integrated in a modular software package called Simufact.premap (prediction of material properties). This concept allows to meet the future requirements of simulations in this field. The precision of the simulation results is determined to a large extent by the precision of the material parameters. For this task interfaces to different material data bases are provided to combine material data for the individual models. An innovative source of material data is e.g. JMatPro of SenteSoft, which computes the all relevant material properties based on the chemical composition for the entire temperature range and for all phases.

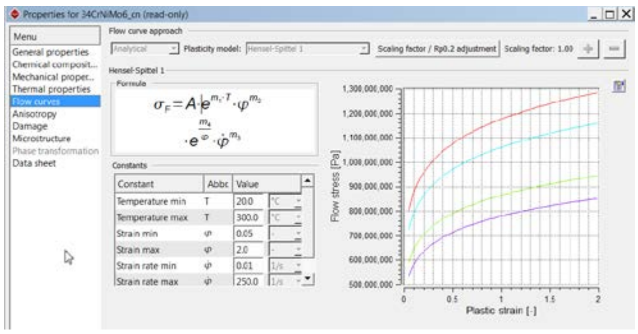

Figure 10: Open material database Simufact.materials

Automatic process control

The control of the open die forging process is another essential component of the simulation system for process chain modelling. The forming of the casted ingot requires a large number of operations in sev-

eral heats. As soon as the formability is lost due to temperature loss the workpiece must be reheated in a furnace. The course of the forging steps determines the soundness of the forging and the microstructure in which the defining parameters are mainly the static and dynamic recrystallisation due to plastic strain. But also at the edges of the workpiece or in the contact zone to the manipulator grips the faster cooling rate causes phase transformations.
The number of individual forming blows can easily reach one thousand. In between the blows and after the pass pause times have to be considered as well as the transport and heating times in between the heats. The time history and subsequently the temperature field should be modelled as precisely as possible since they are determining the force requirement as well as the final product properties. Moreover, depending on the strategy the workpiece is subject to different reaction movements, which are to be considered.

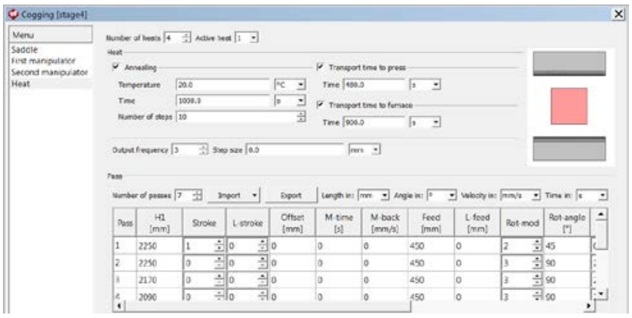

Figure 11: Cogging kinematic for automatic control of the entire process in Simufact.forming.

Hence, in the last years an adaptive control was implemented in Simufact.forming providing an automatic cogging simulation for several heats. For this purpose a pass plan is roughly to be given (Fig. 11), the handling with one or multiple manipulators, the number of blows for each pass, etc. are automatically determined. This is possible due to the continuous evaluation of the simulated process on the basis of the geometry, forces, strains and temperature among others. These characteristics are used as criteria for the further course. Thereby the elasticity of the manipulator can be considered. The kinematic control is a modular concept and can be individually extended, even to the point of self-optimizing systems. Given that, each user can implement his special process particularities. This special kinematics module of Simufact.forming provides an economic analysis of open die forging processes without user interaction and empowers the user to study a large number of variations to increase the process stability and to determine the main influencing factors on the final product properties.

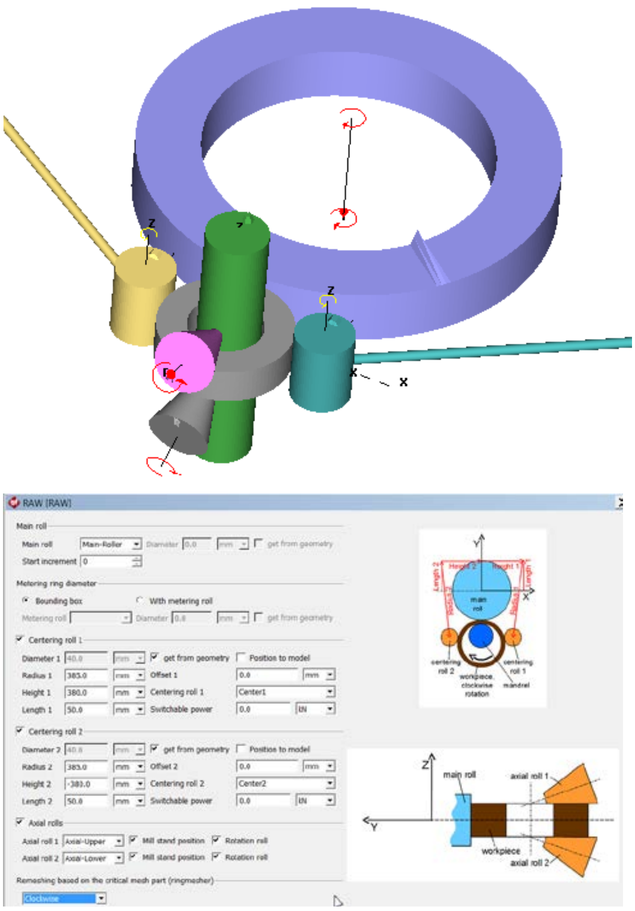

Figure 12: Ring rolling module and automatic control in Simufact.forming.

The presented possibilities are transferable to ring rolling processes, in which starting from the ingot the upsetting, pre-forging and piercing are modelled prior then the simulation of the ring rolling process in which the pre-form is rolled to its final shape. During these steps the microstructure is modelled. For the ring rolling process also all relevant process control mechanisms are implemented in the ring rolling module of Simufact.forming (Fig. 12). Based on the development of e.g. the ring diameter and force among others, the control parameters are automatically computed in the simulation program and used for the control of the rolls. The precise representation of the kinematics combined with the use of Hexahedral-elements with an elasto-plastic material law guarantee for a precise computation of the ring deformation and rotation and subsequently a precise computation of the residual stresses and the microstructure. This is particularly important for thin rings which can bulge and dent due to the remaining residual stresses as soon as the ring is released. After the cooling process (Fig. 13) the ring can be cut in Simufact.forming to its final geometry and then be subjet a heat treatment simulation. The so gained knowledge of the entire process chain can be used for further optimisations of the ring manufacturing.

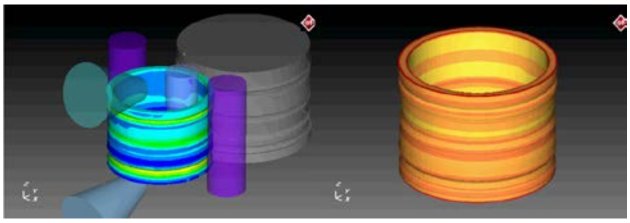

Figure 13: Profile Ring rolling simulation (left) and cooled down ring (right).

Conclusion

In this paper the current developments of the simufact engineering GmbH in the field of process chain simulations of large incrementally formed components have been presented.
Newly developed interfaces provide the possibility to import simulation results from casting simulations to be used as initial conditions for open die forging simulations. With the new material data infrastructure in Simufact.forming material properties based on the local concentration of alloying elements can be considered including mixed phases and the resulting material properties can be computed. Depending on the physical effects and the materials modelled different metallurgical models are applied. Their management is carried out by an new material data management tool. Due to its flexibility and open structure individual amendments are quickly possible. The control of the cinematically complex processes cogging and ring rolling is provided by Simufact.forming using already available control modules. Through this it is possible to quickly set up a model based on the planned pass sequence, which allows to examine more process variants. The applied hexahedral element technology guarantees for the required highest result quality.
A target is to lay out manufacturing processes with the highest possible resource effectively and high process stability and optimised final product properties. This requires the understanding of the interactions of the individual manufacturing steps which allows to adjust product properties at an early manufacturing stage and to develop countermeasures for potential defects arising from previous steps. Thereby the milling and heat treatment can also be considered. Simufact.forming provides a common platform for all these manufacturing steps. The product properties are predicted by applicable material models, which are consequently further developed and extended. Due to its open and flexible structure and data base infrastructure Simufact.forming is prepared for future requirements and is continuously further developed according to the state of the science.

References

Groche, P., Fritsche, D., Tekkaya, E.A., Allwood, J.M., Hirt, G., Neugebauer, R., 2007. Incremental Bulk Metal Forming. CIRP Annals, 56-2, p. 635-656.
Kang, S., Kim, S., Lee, Y., 2010. Application of Modified Hydrostatic Stress Model to Internal Void Crushing in Foring of Large-Scale Ingot. Proceedings of the 13th International Conference on Metal Forming, September 19-22, Toyohashi, Japan, p. 314-317.
Mendoza, V., 2010. FEM Analysis of Defects and Microstructure Evolution during Hot Working of Specialty Alloys. Proceedings of the 13th International Conference on Metal Forming, September 19-22, Toyohashi, Japan, p. 106-109.
Mc Bain, G., Barth, H., Huang G., Wohlmuth, M., Schafstall, H., 2012. Simulating Incremental Bulk Forming Processes with Flexible Kinematics Considering Microstructure Changes, Blowhole Reduction and Automated In-process Control. Proceedings of the 10th International Conference on Technology of Plasticity, ICTP 2011, September 25-30, 2011, Aachen, Germany, pages 220 -223.
Schafstall, H., Barth, C., 2010. An innovate Approach to Automated Simulation of Full 3D Ring Rolling Processes and Other Incremental Forming Processes. Steel research international, vol. 81, no. 9, p. 202-205.
Terhaar, J., Poppenhäger, J., Bokelmann, D., Schafstall, H., Kelkar, K., 2010. Considering the solidification structure of var ingots in the numerical simulation of the cogging process. 7th int. Symposium on Superalloy 718 and derivates, Oct. 10-13, 2010, Pittsburg, US.
Utsunomiya, H., Yukimoto, T., Sakai, T., Suzuki, S., Nakajima, H., 2010. Pore Closure in Multi-Pass Cold Rolling of Lotus-Type Porous Copper. Steel research international, vol. 81, no. 9, p. 158-161.
Xiu-quan, C., Yu-lin, H., Qin-xiang, X., Bei-gu, K., Wen-xuan, C., 2010. Closing of Central Cavity in Shaft Heavy Forging. Steel research international, vol. 81, no. 9, p. 330-333.
Niyama, Uchida, Morikawa, Saito; A method of shrinkage prediction and its application to steel casting practice; AFS International Cast Metals Journal; 1982.