VIRTUAL DESCRIPTION OF BULK SHEET METAL FORMING PROCESSES CONSIDERING MULTIPHASE MODELS REGARDING THEIR ADJUSTMENT OF PRODUCT PROPERTIES

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ABSTRACT: the ongoing trend for lightweight constructions requires for the prediction of local product properties in addition to the feasibility of the applied manufacturing process. This calls for the implementation of advanced localized material models to FE simulation tools used for these virtual developments.
The product range considered is from the forming of micro components with tolerances of a few micrometers to thick sheet metal forming processes. This paper explains how the growing model depth (vertical scaling of process simulations) is creating increased demands on the precision of the simulations of the fundamental result values. The application of microstructure models demands a high quality and density of scalar result values which forces the user to apply fully coupled models which consider the history of the manufacturing process steps. Additionally, the description of the stochastic scatter of the initial and other process parameters is required for the robust manufacturing process design. Some approaches for this requirement are presented in an outlook, indicating how these could be met in one simulation environment und future developments sketched.

KEYWORDS: micro forming, bulk sheet metal forming, crystal plasticity, multi-scale models

1 INTRODUCTION

Most structural components are typically designed today on the basis of structural simulations using the CAD geometries of the design process. The verification of the producibility and the manufacturing process layout is carried out independently in manufacturing process simulations.
Challenging lightweight and material saving requirements demand for specific local component properties to be created in the manufacturing processes. These adjusted local properties are the basis to optimize the structural design to increase the component performance. Such optimized manufacturing processes demand an interdisciplinary approach to better adjust the individual manufacturing process steps. This paper demonstrates these developments in the field of the bulk sheet metal forming processes which are modeled with solid elements to provide highly precise predictions of the physical properties.

2 PROCESS CHAIN

The properties and functionality of a component are, besides its macroscopic form, surface and material, defined by the microstructure – the structure and defects in this structure. The structure, which is already defined after the first shaping – the initial solidification from the melt – is subsequently modified in all further processing steps such as forming and heat treatment and determines the final production properties in the end. Especially in the case of modern, highly efficient process chains and tailor-made materials it is a decisive factor to optimize the development of the structure along the production process and to provide models for the quantization of the correlation of structure and properties. A typical simple process chain is shown in Fig. 1. This can be extended from the molten material up to the heat treated part and its final structure simulation under loading conditions.

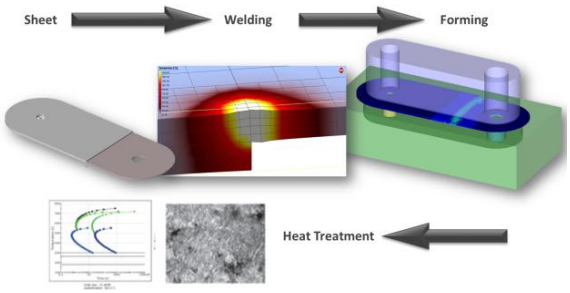

Fig. 1 *Process chain of a tailor-welded blank*

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The impact of the previous stage (welding) is shown in Fig. 2. The critical area for the formed tailored blank is at the outside of the weld path where the largest strains and stresses occur.

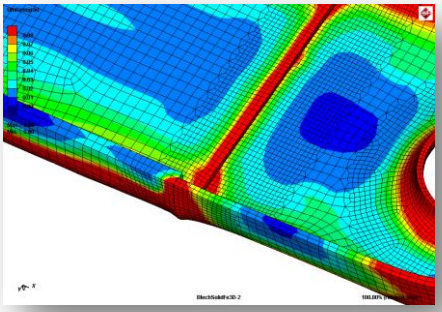

Fig. 2 *Welded and formed tailor-welded blank*

A similar chain with reverse order (first forming, then welding) is applied in the manufacturing of large tubes where thick sheets are bent in multiple steps and finally are seam welded - see Fig. 3. The phase changes during the welding process play a significant role for the quality and safety of the pipes manufactured.

The understanding of the impact of previous process stages for the final properties is getting ever more important. Only the relevant properties and information have to be taken into account, but determining them can be challenging. This needs a closer cooperation of different disciplines and faculties, especially casting, forming, material science and metallurgy. Simufact Engineering GmbH cooperates with many national and international partners to combine the existing and currently developed solutions, which often are isolated, on a single platform Simufact.premap (Prediction of Material Properties). This platform integrates and couples material information and automatically couples different models to perform process simulations with Simufact.forming or Simufact.welding respectively implementing multiscale material models. Particular priority is given to the simple and intuitive usage of the GUI based on a modular, flexible and open material database concept allowing for user-friendly expansion of the material data.

The mechanisms relevant for metals take place on various length scales. Usually the different mechanism on the nanoscale (precipitation, dislocations, twinning), on the microscale (grain boundaries, crystal structures), mesoscale (grains, pores) and the macrostructure (polycrystal) are applied, whereas the mechanisms of the smaller scales are depicted on the higher scales as densities and field sizes.

In many cases only the consideration of all relevant mechanisms on the different length scales in the framework of a multiscale approach allows a broad understanding of the material in production and application. In this context, it is important to identify sufficiently precise the initial state, from which the metallurgical mechanisms can be described continuously. From this starting point (e.g. the homogeneous, stress-free melt) all further process steps can be developed schematically. Examples include the influence of precipitations, such as titanium nitrides or manganese sulphides that may evolve in the melt and may influence the grain size, the recrystallization behavior, the machinability and ultimately the component properties during the further process.

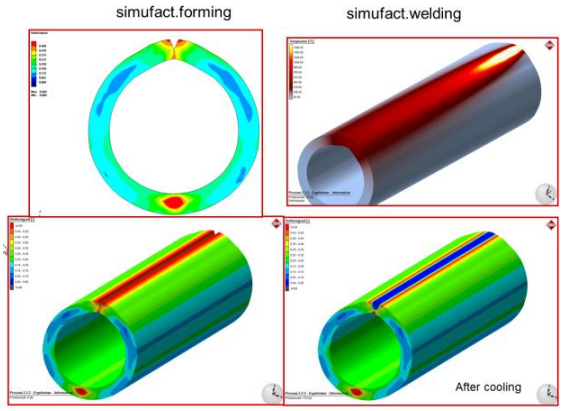

Fig. 3 *Formed and welded pipe*

Apart from the description of the phase equilibria, which primarily depend on the chemical composition and temperature and can be characterized by Gibbs' energy, mainly the kinetics of precipitations, the resolution, the recrystallization and phase change play a major role. As real processes normally take place within a limited time period, thermo-dynamical non-equilibrium states are generally present and hence can be considered to be thermically "frozen". There are appropriate models with different resolutions and accuracy. The related model data are stored in thermodynamic databases like ThermoCalc. These models find their limits primarily in the fact that a complete spatial resolution and a consideration of all effects including the local chemical composition lead to unacceptably long computing times.

2.1 Material database

The new material concept in simufact is based on a flexible multiphase model which allows the definition of phase dependent material properties (physical data and flow curves) as shown in Fig. 4. The phases can be standard phases like Austenite, Martensite, Ferrite, Perlite Bainite, or others like special Carbides etc.. The current material data are calculated based on a mixture rule of the phase distribution.

The phases are depending on the chemical composition, among other factors. Therefore, also the

initial chemical composition is stored at the integration points or is used from a casting simulation as shown in Fig. 5.

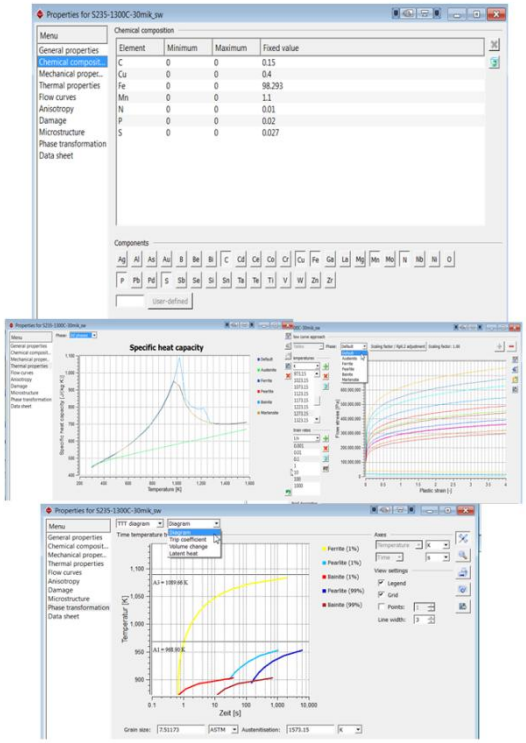

Fig. 4 *Phase dependent material properties and chemical composition*

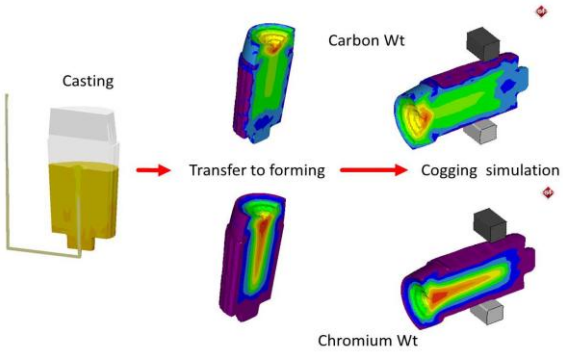

Fig. 5 *Chemical composition after casting*

This is the basis to additionally take diffusion processes and their impact on the properties into account. Therefore we will also add the calculation of the diffusion process during the thermal and mechanical solution with the dependencies as shown in Fig. 6 in the future.

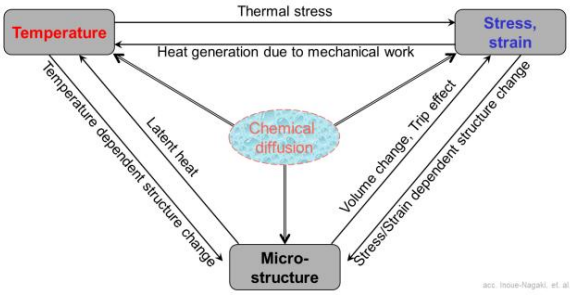

Fig. 6 *Fully coupled simulation with kinetic models*

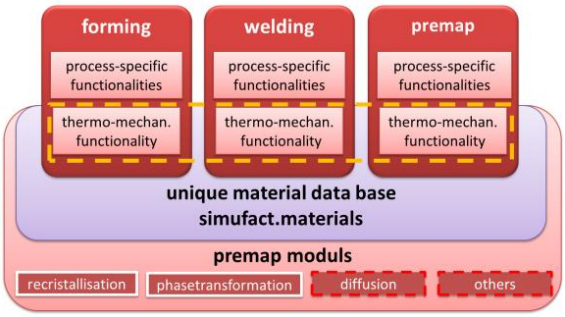

Fig. 7 *Fully coupled simulation with kinetic models*

The material data concept and database is used in all our moduls as shown in fig. 7. This allows a continuous simulation of the different process stages in a process chain.

2.2 Implementation of phase transformation models in Simufact.forming

A phase transformation model was implemented to Simufact.forming which simulates the phase changes, the latent heat and volume changes during the phase transformation as well as TRIP effects. These computations are fully coupled into the solver scheme. Hence, the locally changing material properties are considered by a rule of mixture based on the current local phase composition. The transformation kinematic is described by TTT diagrams. The solving is carried out with adaptive time steps so that whenever a phase change takes place the local temperature changes do not exceed 1K per time step. The transformation itself is modelled based on the description of Johnson-Mehl-Avrami-Kolmogorow as shown in Fig. 7. It is internally approximated by a step function which computes the transformation quasi-isothermal in each of these time steps. The transformation kinematic and therewith also the TTT diagrams do depend on the grain size. Now, the average grain size of the workpiece can be considered only, but current investigations are aiming at considering the local grain size distribution.

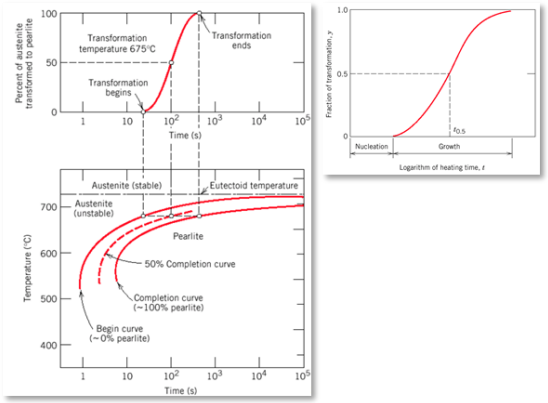

Fig. 8 *Interpretation of a TTT-diagram based on Johnson-Mehl-Avrami-Kolmogorow*

One process chain application of this model is the press hardening process which combines the deep-drawing process with the hardening process in one tool setup as shown in Fig. 8. This sheet metal forming and hardening process is simulated with Simufact.forming fully elasto-plastically coupled using hexahedral volume elements to predict the final phase composition, hardness distribution and final geometry after spring-back with high precision. The forming dies are modeled heat-conductive and the cooling channels are considered.

The simulation model helps to design the process and tooling concept in such a way, that there is no region in the sheet where the martensitic transformation starts before the deep-drawing process is finished. This avoids the formation of phases of limited ductility and subsequent failure. On the other hand the cooling rate must be high enough, so that the martensitic transformation will take place during the cooling phase at the BDC of the dies. The predicted properties are the local phase composition, hardness and yield stress.

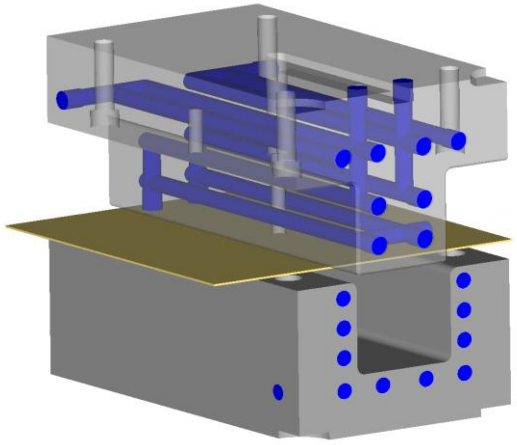

Fig. 9 *Simulation model of press hardening process*

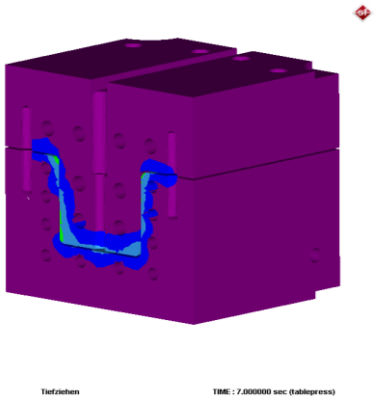

Fig. 10 *Temperature-distribution in the dies with cooling channels at the end of the process*

During welding and heat treatment simulations the phase transformation effects are similarly considered. Additionally, austenitization is modeled for these processes, now with a simplified model. Developments similar to the models presented above are carried out to consider the diffusion and dissolving processes described with TTA diagrams (Time-Temperature-Austenitization) based on the diffusion and dissolving processes.

To model the material properties at an even smaller scale various models describing the material behavior at the nano-scale have been developed. Due to the high computational efforts their scope of application is very limited. Current developments which resulted in higher computational efficiency makes such models applicable for a broader range of processes. The next chapter will present newest research activities to couple nano-scale models with the FE-solution based on simufact.forming.

3 Linking FEM with nano-scale microstructure simulations

As shown above, there are at least in the academic sector and, also sporadic in industrial application, physically-based model approaches and methods, which are suitable for the high resolutions needed in the microstructure modeling in the meso-, micro-, and nanoscale. What is common to all of the mentioned approaches is that a significantly higher amount of information goes hand in hand with a considerably higher effort in terms of computing time. Hence, for some time now a considerable amount of work has been done in establishing intelligent databases and expert systems to accelerate the development of high-performance materials as needed in lightweight construction application in the sense of the ICME-idea.

The NMAB report /2/ emphasizes the key role of such systems in collecting, cataloguing and archiving materials and their “critical properties” as they are essential for an application of ICME. Still the

study does not mention how such a database has to be structured and how the acceleration of development work can be performed.
Incidentally, many solutions have proven themselves to be too costly and inefficient if you pose questions on different standards (and their further development), on the well-known broad scatter of measurement results of different measuring devices or with different methods for same materials and, finally, the less-known (process) history of material samples. /3/

And, last but not least, also the knowledge about the spatial distribution of the local properties or conditions in the inner structure (e.g. morphological features) on different length scales is of high importance for the determination of local and global material properties. /4-6/

Among various statistic approaches, which have been examined for the solution of the task, two-point statistics has distinguished itself as an efficient and sufficiently accurate method. A two-point statistics $\boldsymbol{f_r^{hh'}}$, is a method to determine the probability density distribution at the beginning and end of a stochastically distributed vector space r, with h and h' as desired conditions at the beginning and end of the vector. Structure characteristics are described as statistical functions. An advantage of treating microstructure functions as stochastical processes is the strictly associated quantification of the variances of the considered structure characteristics. These can provide, also in relation to other known (global) imponderables (process variation, batch influences, measurement uncertainties, sample location), statements on the total variance of the examined capability characteristics, even – using appropriate computational methods – practically in real time. "Material informatics", a new field of research, is in an early stage in its development, but will quickly gain importance due to the introduction of modern IT-tools such as image-based search engines, data-mining, machine learning and crowd sourcing. The following figures exemplarily show possible development areas and first results (figures 11–14).

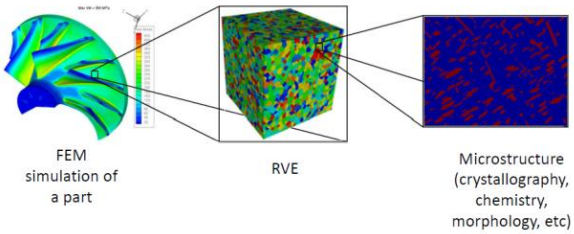

Fig. 11 *Basic idea of multiscale simulation from macromodel to RVE method to statistically based nano-scale "material informatics" according to Kalidindi.*

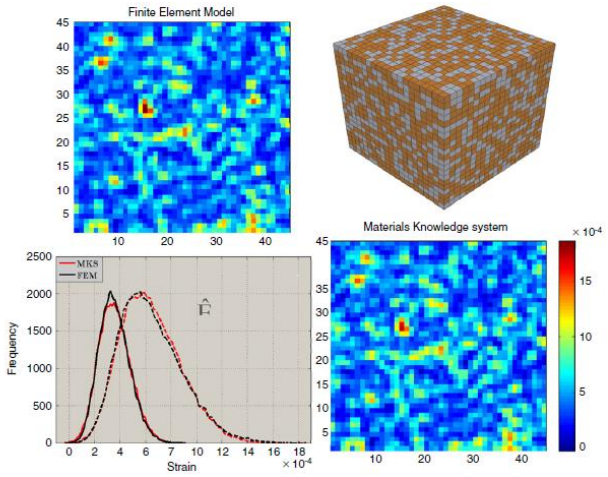

Fig. 12 *Contrasting and good concordance of complex FEM-based RVE calculations of elastic field sizes in a two-phase material with results from a fast statistical calculation of a MKS system according to /1/*

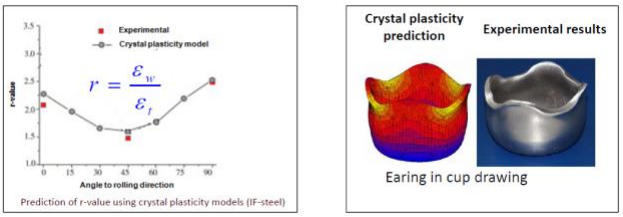

Fig. 13 *Left) achievable quality of results for the forecast of r-values in anisotropy models according to /7/ and right) forecast of earing in deep-drawing in comparison of CPFEM and experiment according to /8/*

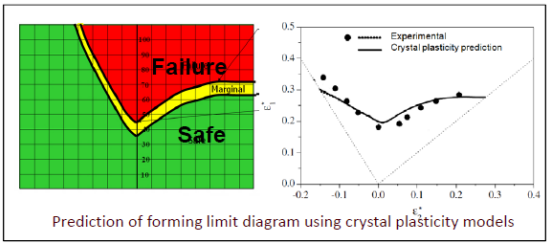

Fig. 14 *Potential application of multiscalar material models for calculation and application of FLC-curves as a boundary condition for FEM models according to /9/*

4 CONCLUSIONS

The implementation of advanced localized material models to FE simulation tools is necessary for the prediction of local product properties in addition to the feasibility of the applied manufacturing process. The coupling of nano-scale models into the FEM will allow a detailed view inside the material behavior and will visualize the influence of the manufacturing process to the texture. The simulation of all relevant and property influencing process stages are getting more and more important for an accurate result. This affords one consistent material database and the same material-models for all steps. Therefore a unique and open database concept were developed which allows the use for forming, welding and heat treatment application as well which covers a big range of substages for sheet bulk-metal forming applications. It will become more and more important in the future.

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REFERENCES

[1] Jitesh H. Panchal, Surya R. Kalidindi, David L. McDowell, *Key computational modeling issues in Integrated Computational Materials Engineering*. Computer-Aided Design 45 (2013) 4–25

[2] Pollock TM, Allison JE, Backman DG, Boyce MC, Gersh M, Holm EA, et al. Integrated computational materials engineering: *A transformational discipline for improved competitiveness and national security.* National Materials Advisory Board, NAE, National Academies Press; 2008. Report Number: ISBN-10: 0-309-11999-5.

[3] Freiman S., Madsen LD, Rumble J. *A perspective on materials databases.* American Ceramic Society Bulletin 2011, 90:28

[4] Milton GW., *The theory of composites*. Cambridge monographs on applied and computational mathematics, 2001

[5] Torquato S., *Random heterogeneous materials.* New York: Springer-Verlag; 2002.

[6] Fullwood DT, Niezgoda SR, Adams, BL, Kalidindi SR. *Microstructure sensitive design for performance optimization.* Progress in Materials Science 2010;55: 477–562

[7] Eyckens,et al., International journal of plasticity, 2009, pp. 2249…2268.

[8] Liu et al. Materials Letters, 2004, pp. 3826…3830

[9] Schmitz GJ, Prahl U (eds), *Integrative Computational Materials Engineering – Concepts and Applications of a Modular Simulation Platform*, Wiley-VCH, ISBN: 978-3-52733-081-2