The potential of accurate material simulation for forming simulation

Frank Padur, Dr.-Ing. Kristin Helas

GMT Gesellschaft für metallurgische Technologie- und Softwareentwicklung mbH
Börnicker Chaussee 1-2, 16321 Bernau, Germany

padur@kocks.de
kristin.helas@gmt-berlin.com

Summary

Realistic material simulation is becoming increasingly worthwhile as part of simulation projects. If tolerances are to be calculated within a few hundredths or temperature variations within a few kelvins, the associated material data and models must also have a high degree of accuracy and match the conditions in the production process. The paper illustrates the influence of experimentally determined data, such as flow curves, temperature-dependent properties and CCT diagrams, and realistic material models, such as the microstructure and transformation model. Possibilities are shown to the user to apply the material knowledge for individual simulation projects, too. Various application examples illustrate the influence of accurate and validated material data sets on the simulation results of forming processes and heat treatments.

Keywords: FEM simulation, material simulation, materials database, flow curves, microstructure model, CCT diagrams, transformation model

1. Introduction

Nowadays, it is possible to create a digital twin for nearly all forming processes. The field of forming simulation belongs to the daily business in the metal forming industry. One reason for the successful establishment is the significant improvement of the accuracy of FEM simulation results in recent years.
Performing forming simulation necessitates material simulation as an indispensable component, as the forming process and material behavior are inextricably linked and should be considered as a unit. Thus, every FEM simulation project for metallic alloys uses material data and models. In most cases, standard material data sets for selected alloys are included within the FEM software. It is important to acknowledge that these material data and models influence the accuracy of the forming simulation significantly. Moreover, users make compromises with regard to the material data: In practice, similar alloys or standard values and functions are applied without knowing the range of validity. That is why the authors want to show the material data sets included in FEM simulation, the influence of material on forming simulation and the possibilities for user to improve their FEM results.

2. A brief overview of material simulation

Material simulation is used to model and predict the behavior of materials in various conditions and environments. It involves simulating the physical properties and behavior of materials under different loads, temperatures and other conditions using mathematical models and numerical methods. Material simulation can be used to optimize the properties of materials, predict their response to external impacts and design new materials with specific characteristics.
To exploit the full potential of material simulation, a wide range of material data and models can be incorporated into FEM simulation by the materials database MatILDa® (see Fig. 1): properties for various metallic materials as well as functions and models to realistically calculate flow behavior, recrystallisation processes and phase transformation. In the context of FEM simulation, material simulation is utilized to calculate temperature distribution, thermal expansion, force and work requirements, grain sizes, phase fractions and hardness. Most important: all of these partial results are used for the calculation of the microstructure and the mechanical properties of the final product.

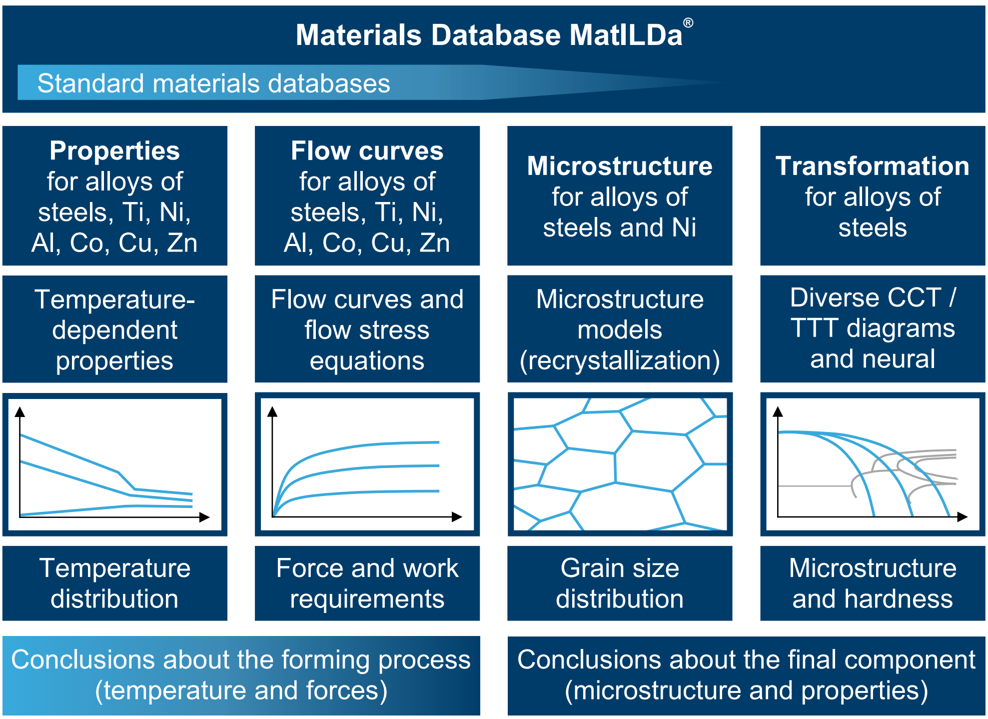

Figure 1: Content of the materials database MatILDa® for material simulation

The functions and models used in material simulation often exhibit a high degree of complexity and typically involve the comparison of different semi-empirical approaches with experimental data. If a particular model demonstrates high agreement with actual observations, it can be incorporated into the materials database for subsequent use. For more details see [1] and [2] about the flow curves, [3] about the calculation of recrystallisation processes with microstructure models and [4] and [5] about neural networks used to calculate the transformation behavior.

3. Material simulation in working practice

Using material simulation in a simulation project is not restricted to those with expertise in materials. First of all, material simulation requires importing material data sets into the simulation software. Often, material data and models can be implemented in FEM software via direct interface. After that, the user selects the alloy and the material data sets are loaded from the materials database. During the FEM simulation, the condition in each node is checked and material parameters are applied as required. Flow stress and temperature-dependent properties are determined using the material data sets. Recrystallization processes (grain sizes and grain growth) as well as phase transformation (microstructure fractions and hardness) are calculated at individual nodes using material models or even neural networks.
Material simulation can be utilized to simulate various forming and heat treatment processes. Table 1 outlines the application of the different functions and model from MatILDa® based on real forming processes and process chains. The high accuracy of material simulation could be proven for these examples with the help of the described validation method (see References).

Table 1: Fields of application of material simulation with MatILDa®

Production process	Material / product	Material simulation*	Validation method	Ref.
Closed-die forging	Inconel 718 / structural component	Properties Flow curves Microstructure	Comparing predicted with experimentally measured grain sizes to improve product quality	[3]
Upsetting and closed-die forging	Inconel 718 / turbine disk	Properties Flow curves Microstructure	Calculation of grain size distribution for optimization of the manufacturing process	[6]
Open-die forging	Ni-alloyed steel / shaft	Properties Flow curves Microstructure	Comparing FEM results with metallographically determined grain sizes and thermographic images	[7]
Heat treatment	Low-alloyed NiCrMo steel / fork	Transformation	Prediction of microstructure fractions and resulting mechanical properties verified based on hardness test	[4]
Bar and wire rolling	Steel alloys / thermomechanical rolling	Properties Flow curves Microstructure Transformation	Temperature control optimization by simulating microstructure	[5] [7]

* Properties = temperature-dependent properties, Microstructure = microstructure model, Transformation = transformation model

To show the high agreement of simulation and experimental results, the authors summarized the outcomes for the heat treatment of a forged fork from aerospace industry according to [4]. Thus, the QForm UK software and the materials database MatILDa® were used to simulate the transformation behavior in depth. Initially, experimental data, such as dilatometric measurements and metallography, was analyzed to develop a material model that could predict the steel's transformation behavior during heat treatment. The material model was developed using a combination of empirical and physical approaches, validated and implemented into the FEM project.
Overall, the transformation model enables the simulation of microstructure and mechanical properties (see Fig. 2). A high level of prediction accuracy could be demonstrated: the experimental results in the range of 273 to 294 BHN are close to the results obtained by FEM simulation in the range of 276 to 280 BHN (see Tab. 2).

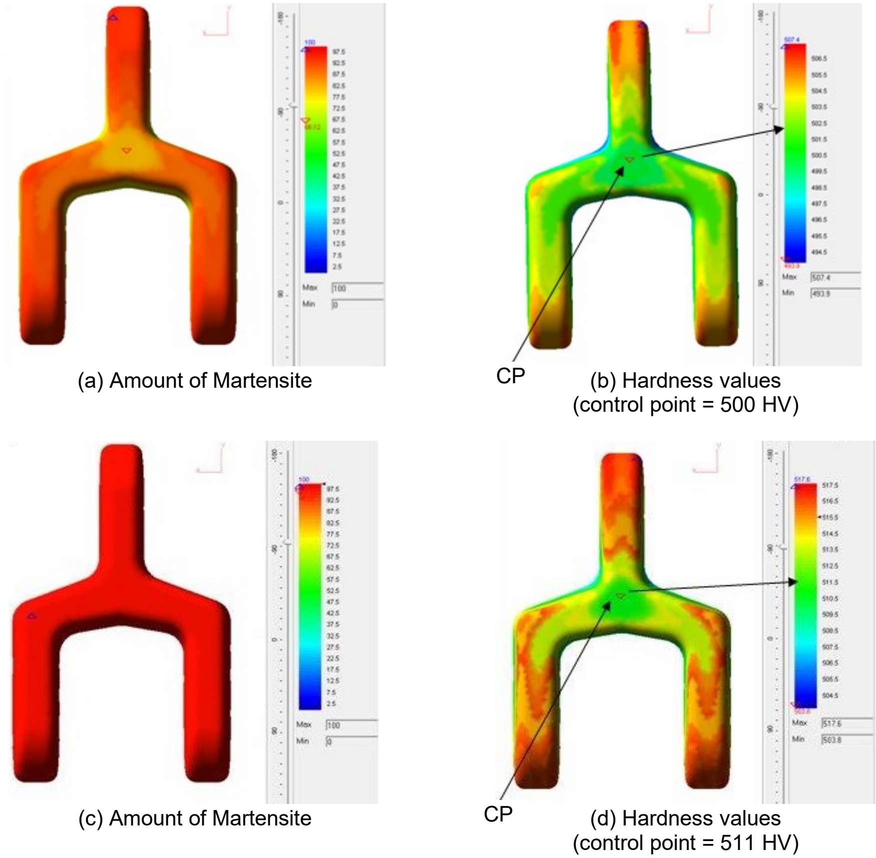

Figure 2: FEM results on the surface of a forged fork with different content of alloying elements: (a), (b) low and (c), (d) medium according to [4]

Table 2: Comparison of the results of simulation and experiments according to [4] after Quenching (Q) and Tempering (T)

Alloying elements	Simulation				Experiment
	Martensite$_Q$ in %	Hardness$_Q$ HV	Hardness$_T$ HV	Hardness$_T$ BHN	Hardness$_T$ BHN
Low content	66	500	290	276	273
Medium content	95	511	295	280	294

Recent simulation projects on hammer forging exhibit additional possibilities by means of material simulation. As it is well known, hammer forging is performed at high strain rates that cannot be realized during material investigations, not even with torsion tests. Thus, the knowledge about flow stress equations offers the possibility to adjust selected parameters to enable realistic material simulation. The simulation yields information on the quantity of hammer blows and the degree of mold filling. A corresponding publication is in progress.

4. Conclusion

Material and forming simulation should be combined with each other to reach simulation results with a high agreement to real forming and heat treatment process. The utilization of the different parts of material simulation (temperature-dependent properties, flow curves, microstructure and transformation model) was explained and examples from industrial forming processes were described.
To use the full potential offered by material simulation, the authors summarize the different aspects users should take into consideration to reach a high agreement between simulation and experimental results:

1. Use material data and models for your specific alloy.
2. Verify the validity ranges of the material data sets to ensure they are suitable for the specific forming process such as temperature, true strain, strain rate or stress state.
3. Ideally, integrate all aspects of material simulation to achieve realistic simulation results.
4. Consider expanding the functions and models according to the process parameters. This should be performed with appropriate materials expertise.

It should be noted, that the acquisition of a whole materials database with a standard interface to FEM software is often much cheaper compared to the acquisition of the complete property spectrum including the creation of material models for only one steel alloy. Overall, the use of a materials database extending the material data sets of standard FEM software is highly recommended.

References

[1] Borowikow, A., Bambach, M. D., Wehage, D.: Einfluss von Fließkurven auf die Berechnung des Kraft- und Arbeitsbedarfs bei der Simulation von Warmumformprozessen. massivUMFORMUNG, pp. 24-29 (March 2021).

[2] Borowikow, A., Schafstall, H., Blei, H., Wehage, D., Borowikow, M.: Integrierte Gefügemodellierung bei der FEM-Simulation mit Hilfe der Werkstoffdatenbank “MatILDa®“. Kompetenzzentrum Neue Materialien Bayreuth (November 2004).

[3] Biba, N., Borowikow, A., Wehage, D.: Simulation of Recrystallisation and Grain Size Evolution in Hot Metal Forming. American Institute of Physics AIP Conference Proceedings, Vol. 1353, No. 1, pp. 127-132 (2011).

[4] Doktorowski, A., Biba, N., Borowikow, A., Wehage, D.: Simulation of the Transformation Behaviour of Low-Alloyed NiCrMo-Forged Steels-from Data Analysis to Material Model. Presentation at the international conference „Neuere Entwicklungen in der Massivumformung“. Stuttgart (2011).

[5] Kruse, M., Schuck, M., Borowikow, A.: Innovations in simulation of microstructure developments. Materials Science Forum Vol. 706-709 (2012), pp. 2170-2175.

[6] Biba, N., Borowikow, A., Wehage, D.: Möglichkeiten und Grenzen der simulationsbasierten Prozesskettenoptimierung. Dargestellt am Beispiel eines Schmiedeerzeugnisses aus einer Nickel-Basislegierung. Internationale Konferenz „Neuere Entwicklungen in der Massivumformung“. Fellbach bei Stuttgart (May 2015).

[7] Borowikow, A., Wehage, D., Blei, H.: Modell zur Gefüge- und Eigenschaftsberechnung für online und offline Anwendungen. XXVI. Verformungskundliches Kolloquium, Planneralm, AT, pp. 123-137 (March 2007).