Technical article

Continuous Process Chain Modeling of low-loss FeSi Sheet for Energy-efficient Electrical Drives

Abstract — **Power density and efficiency of electrical drives are a direct result of the materials used, predominantly the electromagnetic properties of the non-grain oriented (NGO) electrical steel. In order to maximize the efficiency and minimize specific local losses it is necessary to link the complex interdependencies between parameters of the processing steps with the resulting textural and microstructural changes. These changes then need to be linked to the resulting electromagnetic behavior of the material, ultimately allowing to accurately determine the definite properties of the soft magnetic components of an magnetic circuit.**

Until now, knowledge regarding these intricate interactions is incomplete, therefore impeding further progress in the improvement of electrical steel. Despite different approaches to link particular microstructural properties with magnetic properties, a precise simulation basis is lacking. Overcoming said problems requires a new approach, most importantly considering a broader spectrum. This new approach of numeric modeling, is based first and foremost on the coupling of micro- and macro scaled model approaches.

The overarching aim is to interdisciplinary combine partial models from the fields of materials engineering, production technology and electrical engineering. The idea is to develop a continuous model that not only considers local behavior models of certain domains inside the area of interest of a magnetic circuit and its associated parameters, but considers the change of relevant parameters during an entire process, e.g., during the production and processing of the soft magnetic material. In order to accomplish this ambitious task, models of the microscopic and the macroscopic world have to be combined to depict complete and overall behavior and property evolution during a process.

This approach enables the extension of numerical simulation by a further dimension. Up to day objectives of numerical simulations are framed through physical conditions of the current state, e.g., an electromagnetic field problem is defined by geometry, excitation and material. The continuous modeling approach adds the pre-history of certain model parameters and their interdependencies. This respective importance results from the retroaction of the application, processing and production to improve the application by adjusting production and processing. The interdisciplinarity of a process extends the dimension of the simulation approach.

By modeling how the different processing steps affect the microstructural properties and thus the magnetic properties, it is possible to determine magnetic behavior solely as a result of the input material and the processing parameters. Moreover it enables the possibility to create tailor-made electrical steels and align the production technology accordingly, to achieve significant improvement for their application as magnetic components in electrical machines.

The DFG-Research Group "FOR 1897 - Low-loss FeSi Sheet for Energy-efficient Electrical Drives" is made up of an interdisciplinary team of researchers from the fields of materials engineering, production technology and electrical engineering from five different institutes of three universities. By joining their respective expertise this complex topic is to be investigated comprehensively over the course of the next years, aiming at improving the material electrical steel and its processing by means of multiscale, interdisciplinary numerical simulation.

I INTRODUCTION

In order to satisfy growing demands for sustainable and resource-conserving mobility, it is necessary to utilize energy from regenerative sources. A main reason for hesitations is the limited operating range, provided by electrical vehicles. Besides the general topics of efficient energy storage and lightweight car bodies, power density and efficiency of an electrical machine itself bears potential for improvement.

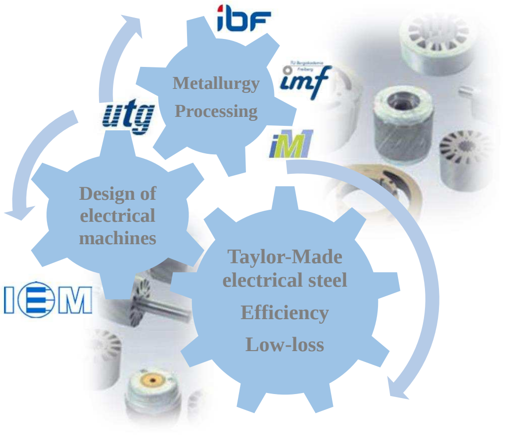

Figure 1: Collaboration between the different technical fields.

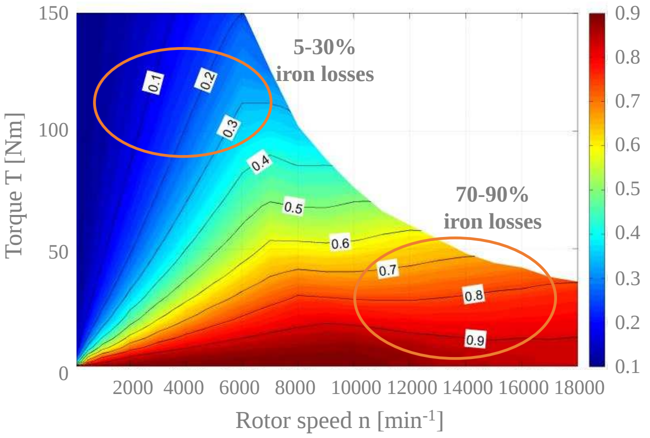

Figure 2: Ratio of iron and copper losses, dependent on rotational speed and torque in an electrical drive system.

Because the potential for improvement by constructive measures is largely utilized, the focus for future progress needs to be shifted on materials design. When converting electrical to kinetic energy in electrical machines, losses are unavoidable. There are different types of losses, but for this research the emphasis is laid on iron losses, because they are substantial for total losses when converting energy in electrical machines. In order to maximize the energetic efficiency these losses need to be minimized. At the same time the power density has to be increased, leading to an imperative necessity for higher rotational speeds and larger numbers of pole pairs. Therefore, higher operation frequencies are required, thus resulting in even greater iron losses, Figure 2. Additionally the mechanical properties for applications in rotating machines and the workability of the product needs to be taken into account during these considerations. However, for electrical steel an optimization of magnetic properties mostly ensues at the expense of mechanical properties. This trade-off usually requires a compromise of these properties

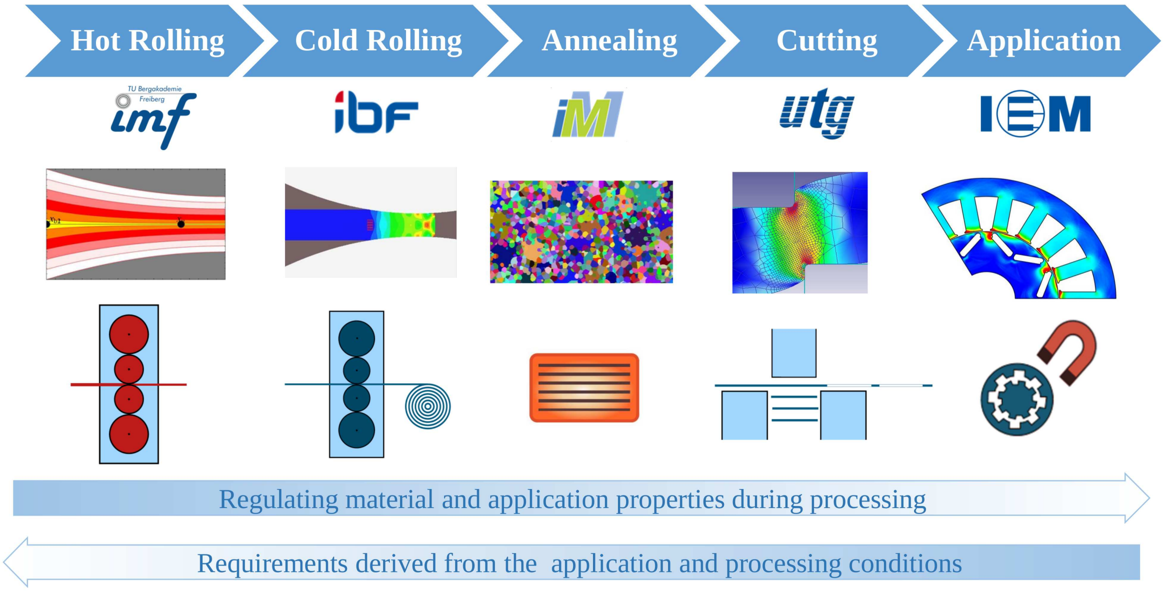

Figure 3: Production and processing of electrical steel.

based on the application priorities. The material optimization regarding both magnetic and mechanical properties as well as workability is in pending need for progress.

Up to this point the main problem is the insufficient knowledge base regarding the correlation of magnetic properties and material properties such as microstructure or texture. Today‘s models for electrical machines almost exclusively include physical coherences. Correlation of the operation characteristics of magnetic components with their causes in production and processing is not consistent, making precise predictions for a not empirically investigated material nearly impossible.

Objective of this research group is a process chain oriented approach to minimize specific losses and maximize power density in electrical drives. The main goal is the development of a continuous model that models the interdependent process steps, their influence on the material properties and their effect on the magnetic behavior of a ferromagnetic material for the application in electrical drives. This final concept would not only be aiding the production and process optimization for higher electrical steel grades, but it would enable the possibility of offering electrical steel to be tailor-made for certain applications. Such a continuous model would allow to computationally reverse engineer the material from precise requests of the construction engineers and adjust the processing.

The DFG-Research Group “Low-loss FeSi Sheet for Energy-efficient Electrical Drives“ comprises an interdisciplinary team, which will investigate and adapt this complex topic over the course of the next years. The project is funded by the German Research Foundation (DFG) and planned for timeframe of six years. It is one of very few research groups funded by the DFG each year and comprises five professors, five institutes, three universities and numerous researchers and technical staff. The participating institutions are the Institute of Metal Forming (IMF), Technische Universität Bergakademie Freiberg, the Institute of Metal Forming (IBF), RWTH Aachen University, the Institute of Physical Metallurgy and Metal Physics (IMM), RWTH University, the Institute of Metal Forming and Casting (utg), Technische Universität München and the Institute of Electrical Machines (IEM), RWTH Aachen University.

II APPROACH

In order to establish a continuous model starting from the input of the thin slab casting to the application in the electrical drives, all intermediate processing steps need to be taken into account, Figure 3. Therefore, these processes are to be studied closely and existing models from the different fields need to be enhanced and in some cases be developed. Additionally a model interface is to be established to allow the partial models of the different sub-projects to be connected and joined in a later stage, while considering problems of different scales, model parameters and related difficulties.

One challenge is the consideration of demands from the different fields and product levels. For example, the final properties for the application level, the workability and operability for the processing levels and the feasibility with a certain material for the materials design. So in contrast to previous research in this field, applying a holistic view is essential.

One of the most important steps in creating this model is the micro-macro-mapping of the material and process parameters with the relevant magnetic properties for the application of NGO electrical steel in electrical drives. Previous research shows that all process steps are interdependent. The occurring effects and characteristic during each production step depend on values from the input state of the material into the respective production step. This circumstance indicates that for the application in the electrical machine, where the magnetic properties are of primarily interest, each processing step is relevant.

Conventional electrical steels are FeSi alloys with silicon contents between 0.2 and 3.2 wt.-% silicon. Regular cold strip thicknesses are between 0.23 mm and 1 mm depending on their application. A high silicon content benefits the magnetic properties. Silicon increases the electrical resistance thereby lowering eddy current losses resulting in an overall positive effect on total losses. But silicon content is limited due to processing factors. A silicon content above 2.4 wt.-% is unusual due to deteriorating workability, especially cold rolling, which is essential to achieve the required small strip thicknesses. These thicknesses are desired because eddy current losses increase with increasing thickness. Another effective measure to improve magnetic properties of electrical steel strip is providing a rather large optimum grain

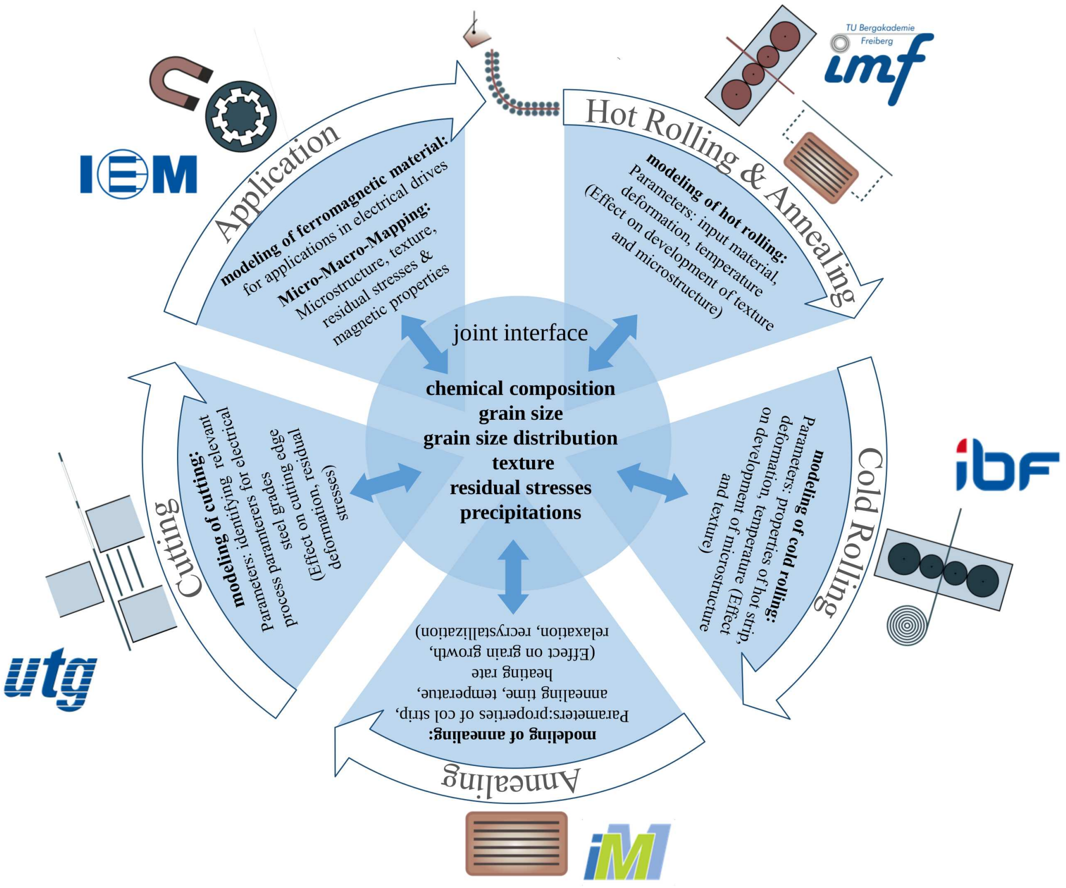

Figure 4: Strategy of the research project: matter of input of the sub-projects to the interdisciplinary, joint modeling interface.

size and a favorable texture. A larger grain size decreases hysteresis losses but also impairs workability.

Objective of this research is a high silicon Fe-Si (NGO). Because of its chemical composition this material shows no phase transition over the entire course of the process chain. The process steps of electrical steel sheet production which are to be investigated include the thin slab casting with hot rolling and annealing of the hot strip, the cold rolling process with different resulting thicknesses, different annealing treatments and the cutting of the electrical steel sheets into final geometries.

The relevant affected parameters for the micro-macro-mapping and therefore focus of the experimental procedures and numerical simulation concern microstructural features such as grain size, grain size distribution along the strip and across the cross-section, local and global texture distributions, impact depths of the cutting edge effects and the influence of residual stresses and their effect on the magnetic polarization, specific losses and permeability.

Within the sub-projects, partial models will be conducted. Information, which is obtained during the investigations as well as the relevant modeling parameters will be contributed to the joined interface for the continuous model, throughout the entire course of the project. In the second period these partial models will be merged to the final model, Figure 4. The quality of the model will be evaluated by comparing computing results with experimental data of a material processed on the trial route.

III SUB-PROJECTS

A Hot Rolling

Hot rolling describes the rolling process of metallic materials with temperatures above recrystallization temperature. This process primarily serves a structural improvement and a thickness reduction of the steel strip, required for the subsequent processing steps. During the actual rolling the input slab gets deformed. Due to the elevated temperatures the required rolling forces in order to achieve an equivalent thickness reduction, are smaller compared with cold rolling. The temperatures further lead to effects of recovery, recrystallization and grain growth immediately after deformation, Figure 6. As a result of these physical processes the microstructure and texture change strongly, dependent on many different rolling parameters for example temperature, characteristics of the roll gap, rolling speed or rolling forces. These parameters result in intricate variations of local and global deformations and temperature distributions. These factors are crucial for texture and microstructure evolution, thus influencing the final material properties.

For the production of very thin, low loss electrical steel grades a progressive hot rolling technique is especially promising. Thin slab casting with direct hot rolling and re-heating results in a homogeneous microstructure, less liquation and thinner hot strips and therefore ultimately in better magnetic properties[1][2]. This technique is objective of many researches and shows promising advantages. However it is not yet commercially adapted [3]. Because of its technical relevance it is subject of this DFG-research. The thin-slab casting with integrated hot rolling and annealing will be the subjective for the experimental investigations and model development of the hot rolling process.

Research shows correlations between microstructure and magnetic properties as well as an influence of hot strip features and resulting cold strip properties. Through trial and error it was observed that an annealing treatment before cold rolling can benefit the electromagnetic properties [4], indicating interdependencies of microstructure of the hot strip and resulting electromagnetic properties. Annealing of the hot strip or variations of coiling temperature influence the proportions of certain texture components [5][6]. The hot strip grain size is a function of the rolling parameters and influences the cold strip grain size as well as grain growth and texture evolution during annealing [7][8]. All of the stated effects are interdependent but have not been studied altogether yet.

In order to create a precise model it is essential to gather information on the physical, mechanical and microstructural effects during the process and to specify the interdependencies. Aim is the investigation on how hot rolling affects the forming of the microstructure and the texture evolution. The identified correlations will be the foundation for modeling the occurring effects during the process. This partial model will describe the hot rolling process as a function of conditions like material data, mechanical data and technological data. Specific material data includes information on flow curves, dynamic and static softening dependent on the grain size, the deformation and the temperature. Some of these information will be collected directly through specific experiments, for example the flow curve . Other effects like dynamic and static softening will be modeled based on the results of further experiments to determine the softening kinetics. Further input data are mechanical technological parameters for the rolling line (rolling speed, roll diameter, distance between stands) and the intended process parameters (initial thickness, deformation per roll pass, temperature before each roll pass, number of roll passes, cooling conditions).

By means of these information it is possible to compute crucial strip features. Most importantly the resulting grain size and texture of the hot strip. Furthermore these information allow to describe the local temperature distribution over the entire strip lengths and cross section and the local stress distribution over the entire strip lengths, cross section and within the deformation zone. Therefore microstructrual and textural changes dependent on different rolling strategies are to be conducted in order to describe the process regarding the relevant parameters for the characterization of the resulting electromagnetic properties. Different modeling approaches on different scales will be used and combined.

Framework for modeling the hot rolling process will be a stratigraphic model based on material flow, analogous to classic plastomechnical models. By dividing the strip thickness into *n*-layers this model can be diversely discretized. To describe the temperature development during the hot rolling process, the model will be coupled with a thermic model. Therefore, basic physical models are incorporated. It will be supplemented with methods of conventional FEM-modeling. In order to model microstructure and grain size development established models such as JMAK-models can be used.

The influence of hot rolling and annealing is tightly interwoven into the processes of cold rolling and final annealing, regarding their impact on microstructure and texture evolution. These sub-projects are entwined by the material flow, target values and modeling approaches. The different institutes are working closely together to create a mutual base for their simulation in order to determine target values and their interdependencies to add to the final model interface, Figure 4. These are the relevant parameters for the magnetic characterization and the micro-macro-mapping.

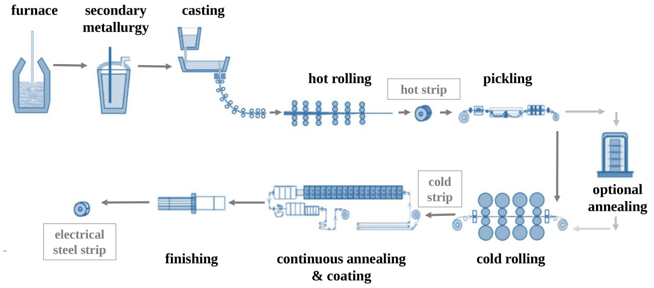

Figure 5: Production of electrical steel.

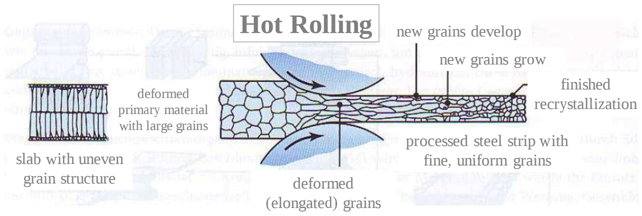

Figure 6: Microstructural processes during hot rolling.

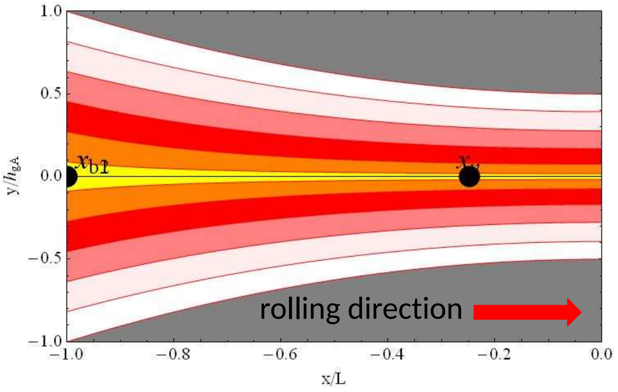

Figure 7: Stratigraphic modeling of hot rolling.

B Cold Rolling

The cold rolling process is the final step conducive to thickness reduction during electrical steel strip production. After this process step the steel strip bears its designated thickness. The influence parameters are largely equivalent to the parameters during hot rolling with the exception of the temperature and its influence on the recovery and recrystallization. However, the deformation condition and microstructure of the cold strip is triggering the recovery and recrystallization during the subsequent annealing step. The development of texture and microstructure during cold rolling, depends on the total thickness reduction as well as the thickness reduction per rolling pass but additionally to a large degree on the properties of the input hot strip [7].

The sub-project investigating the cold rolling process pursuits the aim to develop a validated multiscale model to determine the texture and microstructure development during cold rolling in

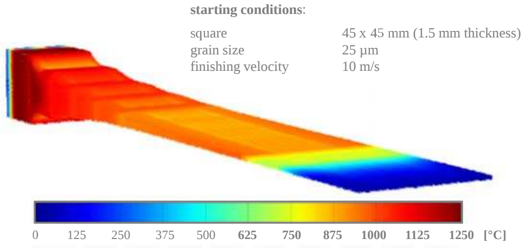

Figure 8: Temperature distribution after hot-rolling.

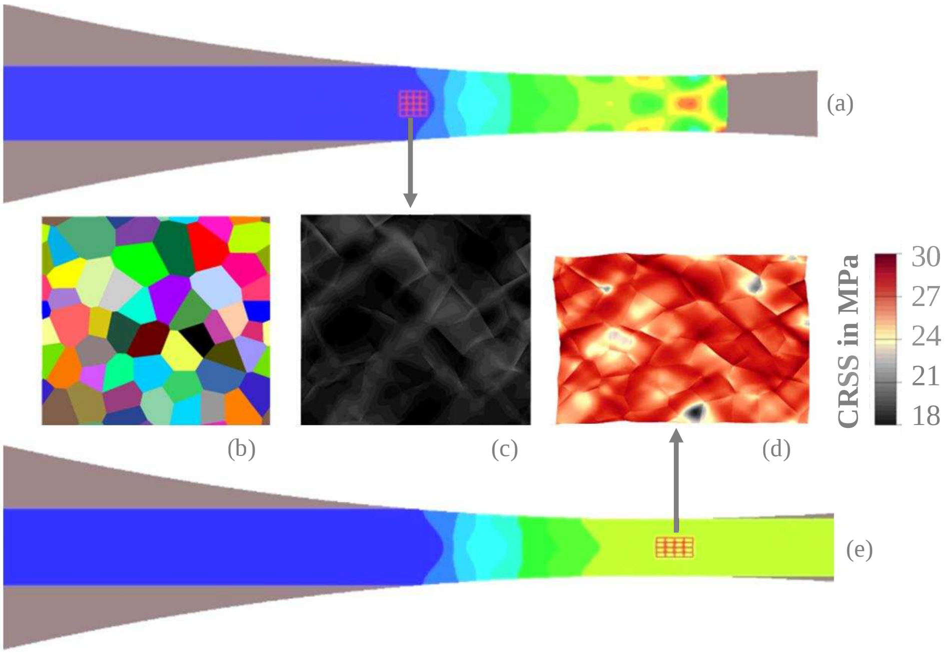

Figure 9: CPFE model of material X60Mn23 in rolling process: a) Macro-model at the time of t0 in Abaqus; b) Voronoi tessellation with 49 grains; c) Micromodel (RVE) at the time of t0; d) Micromodel RVE at the time of t1; e) Macro-model at the time of t1.

dependence of the hot rolled strip conditions as well as the process parameters during cold rolling (total thickness reduction, thickness reduction per pass). In cooperation with the preceding and subsequent sub-projects, i.e., hot rolling and annealing, the model is to describe the whole process of electrical steel strip production, up to the potential delivery to a customer, where the steel strip is to be made into electromagnetic components (corresponding sub-project D). When modeling an entire process chain on different scales, dependencies between microstructure and texture evolution as well as spatio-temporal changes of thermomechanical values need to be considered.

To describe the texture and microstructural changes during cold deformation different model approaches are currently used. So called "full constraints Taylor-Models" [9] are especially valuable because the texture can be computed within an integrated FEM-simulation while still requiring rather small computational power. Practical disadvantage is the oversimplification that every grain experiences the same plastic deformation. More complex models, like the "Viscoplatic Self-Consistent Model" (VPSC), the "Advanced Lamel Model" or the "Crystal Plasticity Finite Element Model" (CPFEM) require significantly larger computational power, but do not rely on this simplification. These models consider the interaction of neighboring grains and the geometric orientation of the sliding systems within the grains [9][10].

The CPFEM approaches can be regarded as a class of constitutive material models . Therefore, they can be implemented directly into finite element codes either in the form of a user subroutine (e.g., HYPELA2 in MSC.Marc, UMATVUMAT in Abaqus) [11], or in DAMASK (Düsseldorf Advanced Material Simulation Kit). The main purpose of DAMASK is the simulation of crystal plasticity within a finitestrain continuum mechanical framework [12]. In the core of DAMASK several constitutive laws of elasticity and plasticity are written. In order to reduce the modeling scale, a grain aggregate which is considered representative of the microstructure and associated texture can be used, namely, a representative volume element (RVE). Figure 9 shows an example of the CPFEM by using a RVE with DAMASK. The displacement boundary condition was obtained from the macro-model (Figure 9 (a), (e)) and then was inserted into the micromodel (RVE) (Figure 9 (c), (d)) as input data. The material data such as crystal lattice (here is face centered cubic) and interaction of slip systems were given in DAMASK, and the micromodel was computed in Abaqus with DAMASK afterwards. As a result, the change of grain morphology can be directly investigated in the micromodel (shown in Figure 9 (d)), and the crystallographic texture (orientation, rotation, etc.) can be visualized by the software like MTEX.

As an intermediate processing step between hot rolling and annealing, it is especially important for the cold rolling process to examine appropriate formats for the data applied in these partial models. Suitable data formats are required to ensure the possibility of a target value crossover to the subsequent process chain step.

C Annealing

The annealing treatment of cold strip is a substantial processing step in the production of electrical steel. During this process the required application properties are further influenced and shaped. Mechanical and magnetic properties are a direct result of the microstructure, texture and material conditions of the annealed cold strip. The pivotal processes affecting the microstructure during an annealing treatment are recovery, recrystallization and grain growth, Figure 10. Recovery is a thermionic activated process due to dislocation reactions. Microstructural changes during recrystallization and grain growth result from grain boundary movements, because of different forces. These physical processes change the microstructure and thus the properties immensely, dependent on the annealing conditions and the preceding processing steps. To achieve the desired properties and impede detrimental side effects, the process steps up to this point are scaled to provide a specific material state that will enable the control of the occurring physical effects. This control can be realized through variations of annealing time, heating and cooling rates, annealing temperatures or atmosphere. Incomplete understanding of the interactions between the processing, physical effects, application properties and material parameters is a problem.

Different research highlights the numerous influencing factors on the evolution of microstructure and texture during an anneal-

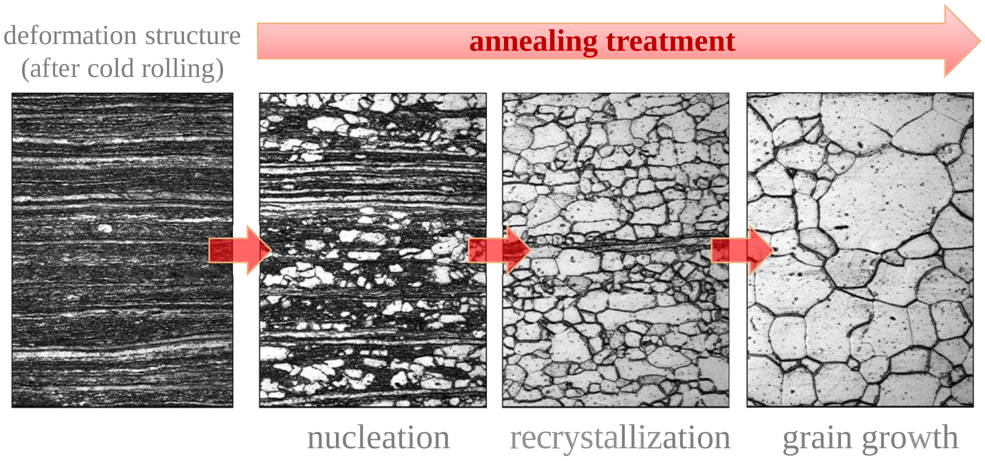

Figure 10: Microstructural processes during an annealing treatment.

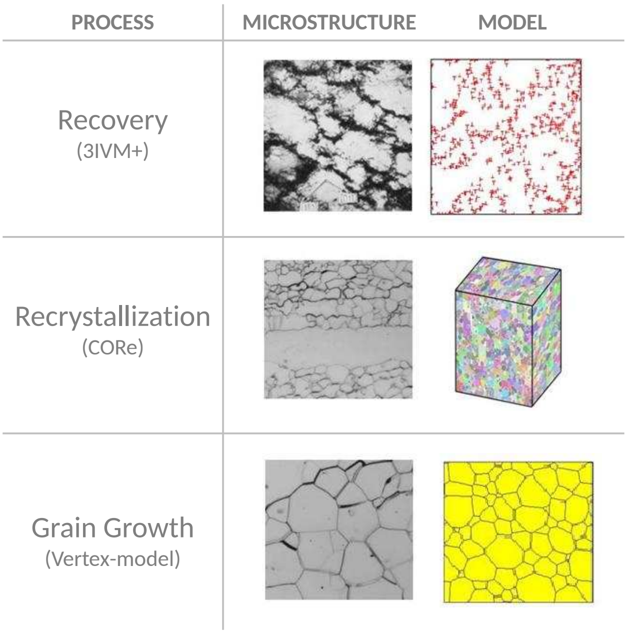

Figure 11: Modeling methods for microstructural effects during annealing.

ing treatment. Higher deformations during cold rolling lead to faster recrystallization during the annealing treatment [13]. Furthermore, the extend of a deformation can trigger additional effects. Selective grain growth during annealing was observed for a material at 95% cold deformation. In comparison selective grain growth did not occur for the same material, during the same annealing treatment, for a 70% cold deformation [14].

Texture and grain size during annealing are further affected by the hot strip properties. Research observed that larger proportion of rotated cubic-textures in hot strip leads to larger proportion of this texture component in the cold strip [8]. Similar behavior occurs regarding the hot strip grain size. Larger hot-strip grain size leads to larger cold strip grain size [7]. Another example for relevant annealing parameters is the heating range, because higher heating rates result in smaller grain sizes [15].

These results were mainly obtained experimental and observed secluded of one another. Within this sub-project an interrelated investigation of the annealing treatment in compliance with the preceding processing steps will resolve the pending contingencies regarding electrical steel strip production. The simulations will include existing models in addition to conducted experiments to model the annealing procedure. The joint model interface will allow for the processes to be modeled in regard of one another in order to deliver relevant target values. These target values and joint experimental will enable the micro macro mapping and thus a rich foundation for the continuous model. Texture evolution can be modeled through static analytic recrystallization texture models [16] and cellular automats [17].

It is necessary to have different models which are aligned to the various steps during annealing, Figure 12). 3IVM+ uses kinetic equations to simulate the movement and annihilation of dislocations. Besides the process parameters like heating rate, annealing time and annealing temperature it uses CPFEM data to generate the morphology. Modeling of nucleation and recrystallization takes place in the cellular automaton named CORe. CORe is a time and place discrete model. The framework is a cubic 3D grid with a scalable sub-grid. Each sub-grid cell has a certain value which represents the recrystallized state. In every time step, the cells change their state in dependents of the surrounding cells. The simulations ends when every cell is in a recrystallized state. From there on, grain growth occurs which is simulated by a vertex-model. These models are also called network models, because the discretization is achieved by a topological network of connected elements. The model is based on the minimization of the free energy through the motion of grain boundary triple junctions. In addition also the curvature of the grain boundaries is consider in the model.

D Cutting

The cutting process of electrical steel strip serves the construction of magnetic components by manufacturing lamellar steel sheets of distinct geometries. These parts are then stacked to form the magnetic core of an electrical machine. A basic cutting tool setup is shown in Figure 14 (a), where the distance between the punch and the die is called cutting clearance (CCL).

The cutting process and its influence on the material is crucial for the performance of the final application. Research shows a high deterioration of magnetic properties because of deformations and the accompanied residual stresses near the cutting edge [18][19][20][21]. Up until now the cutting process has never been adjusted to the specific needs of electrical steel production, especially maintaining acceptable magnetic properties. A high silicon content leads to better magnetic properties but it leads to high wear of the cutting edges when producing a large amount

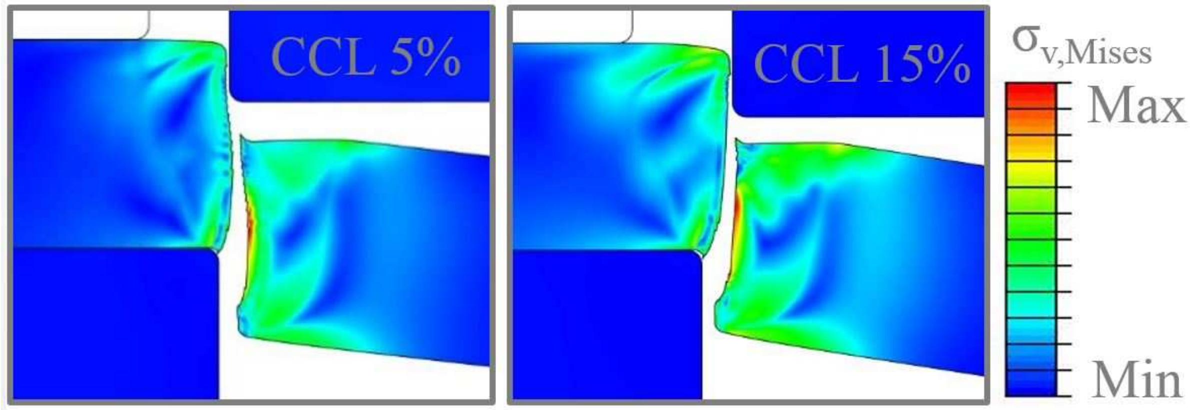

Figure 13: Influence of a CCL variations on the resulting stresses after material failure.

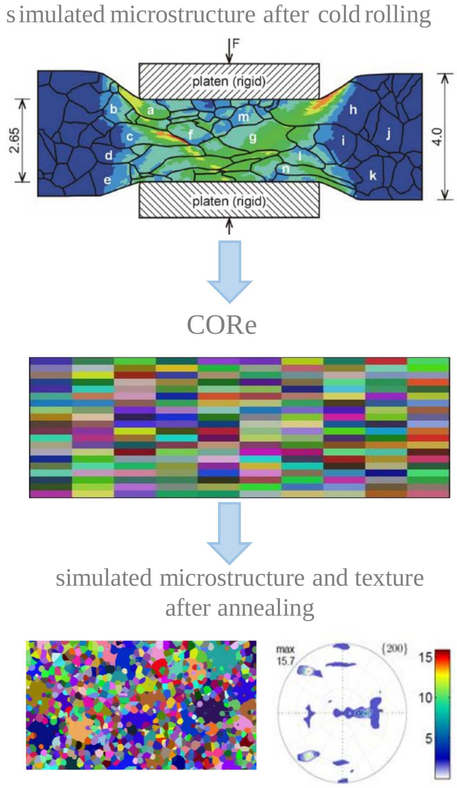

Figure 12: Modeling methods for microstructural effects during annealing.

of parts [22]. Small sheet thicknesses and large grain sizes decrease losses but interfere with the cutting mechanisms, leading to a totally different deformation and failure behavior compared to standard steel grades (intercrystalline clean-cut in Figure 14 (b)). These coherences illustrate the need to take all processing steps into consideration. Hence, not only the magnetic, microstructural properties of the annealed cold strip are important to the application, but also its applicability to the cutting process and how the steel strip is affected by it [23][20].

Research on this topic shows a correlation of stresses resulting from the cutting process with magnetic deterioration[24][25]. Accordingly, smaller deformations in the area of the cutting edge lead to smaller distortion of the material and thus, to better magnetic properties. Losses and hysteresis shapes are therefore highly dependent on cutting tool parameters (clearance, edge proportion) as well as cutting technique (e.g. shear cutting and fine blanking).

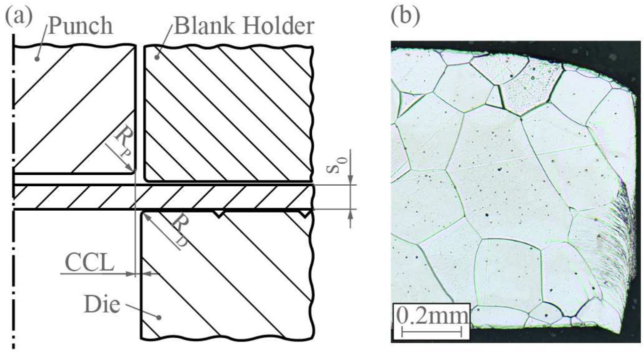

Figure 14: (a) basic tool setup, (b) cutting surface of electric steel.

Up to this point the shear cutting simulation is mostly used to predict the influence of these process parameter variations on the resulting cutting force, Figure 13. Also the relation between the material‘s anisotropy and the part geometry has been investigated. The prediction of the distribution of the characteristic cutting surface parameters is still a big challenge when it comes to the simulation of the shear cutting process. This is because of the difficult numerical description of the failure behavior in between the two cutting edges. Although the point of material failure has an impact on the stress distribution right next to the cutting surface, it can be neglected in comparison to the overall stress distribution change when e.g. another cutting clearance or cutting edge radii is chosen. The residual stresses left inside the electric sheet metal after blanking with different process parameters have not been investigated yet.

Due to the large grain size (up to $100\,\mu$m) compared with the dimensions of the used cutting clearance ($30 - 50\,\mu$m at 0.35 mm sheet thickness) a classical continuum mechanical point of view is difficult, figure 14 (b). Therefore, an improvement of the existing shear cutting models is inevitable in order to even start identifying correlations with electromagnetic properties. This sub-project targets the investigation of the influence of the cutting process on the magnetic properties. Aim is the creation of an experimental based meta-model of the cutting process to describe the microstructure and mechanical properties through interpolation algorithms. Micro-macro-mapping, as described in E, will correlate relevant factors of the cutting process with the affected magnetic properties. Main goal is the identification, evaluation and optimization of cutting parameters that can be influenced and controlled during processing, in order to optimize the cutting process and minimize its detrimental effects on the magnetic properties.

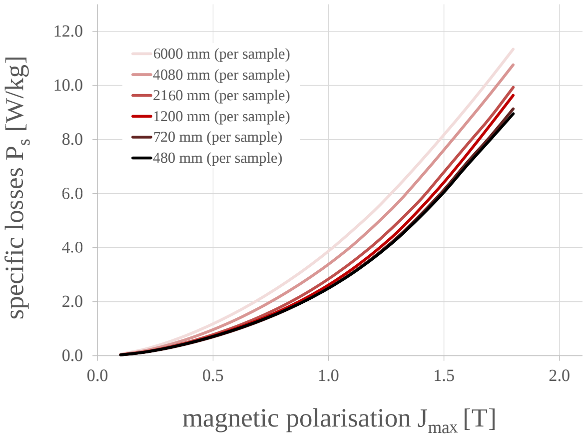

Figure 15: Losses dependent on the proportion of cutting edge for samples with the same size at 100 Hz (guillotine cut).

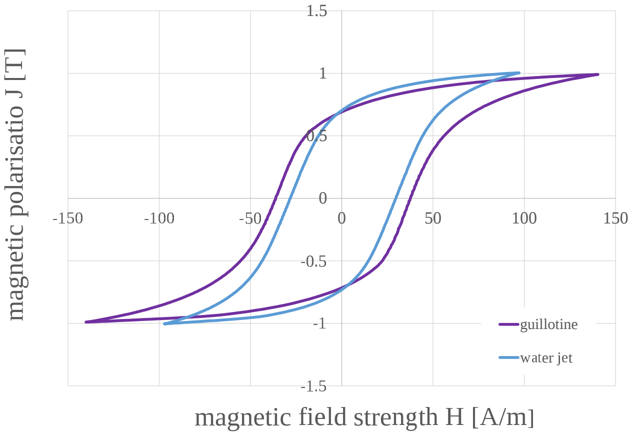

Figure 16: Hysteresis of samples of the same geometry cut with different methods for 1.0 T, DC.

E Application

As thoroughly discussed, electromagnetic properties as well as mechanical properties are of primary concern for the application of ferromagnetic materials in electrical drives. The intrinsic material properties are crucial for losses and efficiency of electrical machines. Traction machines in particular require high frequencies and are operated in saturation of the magnetic material. Due to continuously increasing demands for higher efficiency and lower losses the optimization of the material and its processing gains more and more importance.

Magnetization and losses are basic values in order to study electromagnetic properties of different materials. The magnetization behavior indicates the obtainable flux density for a specific magnetic field strength. In combination with the current coverage, the flux density within the air gap provides the torque. Hereby, the magnetic utilization can be described as a result of the magnetization behavior.

Generally two different motivations regarding the application level are addressed in this research. One motivation arises from the current state of models for electrical drives in general. These models are based on construction parameters, physical parameters and on electromagnetic data for the ferromagnetic material. The main problem is the simplification of the magnetic behavior of the material. Based on the requirements for high frequencies and operation in saturation, present methods of characterizing the material are deficient. Ferromagnetic materials are generally tested with sinusoidal field patterns for a frequency of 50 Hz and two set magnetic flux density values. Thereby all additional effects of the operation range for the material are neglected. A comprising characterization of the material behavior is therefore necessary, considering more complex effects. An example for currently disregarded effects are harmonics. Because of the operation excitation in saturation, field waves of the third harmonic are generated [26]. Further harmonics are caused by allocation of stator windings and high supply by power electronic inverters.

Another simplification when testing the ferromagnetic material is the disregard of the deterioration of the magnetic properties in consequence of the cutting. Figure 15 shows that an increasing amount of cutting edge per set sample size, deteriorates the electromagnetic properties significantly. The relevance of cutting edge effects can even impair models with prototype machines, when compared to serial production. This is due to the fact that different cutting techniques deteriorate the magnetic properties to a different extend, as shown in Figure 16. An accurate modeling of the final application is only possible if the electromagnetic properties of a processed material can be accurately modeled. Therefore precise understanding of the material properties, the processing influence and the resulting electromagnetic properties needs to be conducted.

The correlation will be conducted by micro-macro-mapping. Conceptional correlations between microstructure and magnetic behavior have been identified. Research connected certain alloying elements, microstructure, texture distributions, non-metallic inclusions, precipitations and residual stresses with general tendencies for the magnetic properties [27][28][29][30]. But a valid mapping of the macroscopic magnetic behavior with the microscopic scale is incomplete, because one problem is the quantitative description of the behavior and the other problem is the isolated observation of certain effects. Only when the intrinsic causes for the macroscopic behavior are understood and quantified, the interdependencies can be modeled and the electromagnetic properties of a material could be directly improved.

All necessary information for the micro-macro-mapping is gathered within the different sub-projects. The information regarding microstructure and texture during the processing is the respective input to the joint interface of each sub-project. By studying the evolution of these features with distinct variations of processing, a copious base of information is collected. Because the experimental analysis are conducted on the same material, applying minor changes to the processing allows to isolate certain effects. For example if two samples are equally processed up to annealing, then are annealed for the same time at two different temperatures, the resulting grain size is a direct result of the annealing temperature. If these samples show an analogous texture but significant differences in their electromagnetic behavior, the electromagnetic changes can directly be linked to the grain size. Thereby an isolated dependence of the processing and the resulting magnetic properties can be achieved.

As discussed in D the deterioration of magnetic properties as a result of cutting edges and cutting stresses have been observed but not yet been studied in depths. Experiments with different proportions of cutting edges provide information to model polarisation over the width of a steel sheet sample [24][31]. These models are important to later use such models on complex geometries. The experiments can further investigate other effects. For instance that some effects are highly dependent on magnetic excitation and frequency. With higher frequencies the influence of cutting deterioration get smaller. For operation flux densities in saturation the magnetization is nearly the same regardless of the cutting edge proportions [31][32]. Valuable information can also be conducted by applying tensile and compressive stresses while measuring the electromagnetic behavior. If the results of the magnetic characterizations are matched with the simulation

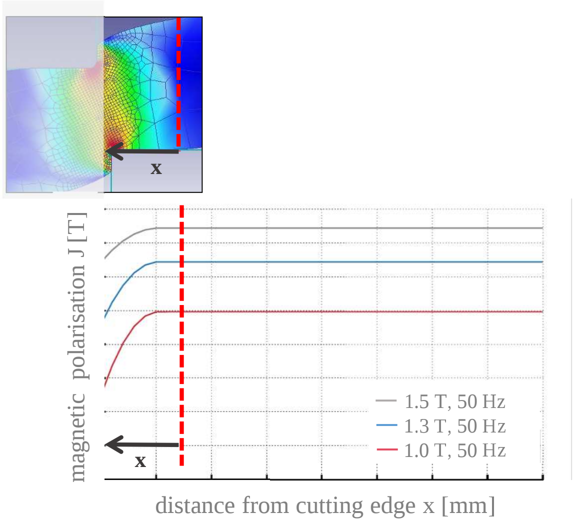

Figure 17: Modeling of polarization over sample width for guillotine cut samples.

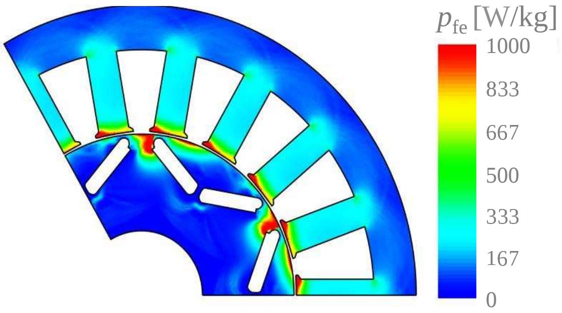

Figure 18: Calculated iron losses for a speed of 18/,000 min^{-1}.

models from sub-project cutting, for example the residual stress state further correlations can be achieved.

Further studies investigate the general effect of stresses on the magnetic behavior of electrical steel. Tensile and compressive stresses can be applied during magnetic testing in order to study their influence. In combination with simulations of the actual stress distribution on a certain geometry, Figure 18 and information on the global effects of stresses on the magnetic properties, a correlation of stresses and the resulting deterioration of the magnetic properties can be achieved.

With a precise model of the application performance, the crossover to the other sub-projects can be realized. The application behavior needs to be described as a function of material parameters, e.g., microstructure and texture, residual stresses, cutting edge effects as well as the application parameters, e.g.,frequency, polarisation, mechanical strain. By connecting all partial models, the main motivation of this research can be achieved, a continuous model which models the material and its relevant properties throughout the whole production and processing chain up to the final application. This will allow to improve materials by adapting valuable knowledge to optimize the production and processing process. Furthermore, emerging from the application requirements, materials could be tailor-made regarding their microstructure, texture and thus certain properties.

IV CONCLUSIONS

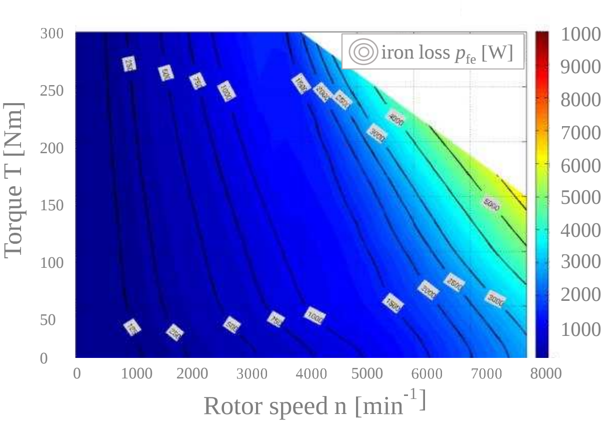

Figure 19: Modeling of iron losses U = 600 V.

Numerical computation of electrical steel production and processing is the next step to enable the improvement of NGO electrical steel, its processing and its applications. The endeavor is challenging and demands an interdisciplinary approach by researchers from the fields of materials engineering, process engineering and electrical engineering. The idea of a continuous model comprising all processing steps and the final application was presented. The research group will investigate and correlate the relevant interdependencies of microstructural, mechanical and magnetic properties and identify the relevant and modifiable process parameters. Partial models will be enhanced and adjusted to a mutual interface in order to develop a joint and continuous model. The validation of this final model will be carried out by applying the model to an input material, while additional processing the subjected material on an experimental process chain and the respective parameters. This comparison will give indication on the quality of the numerical computation and will aide further improvement.

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