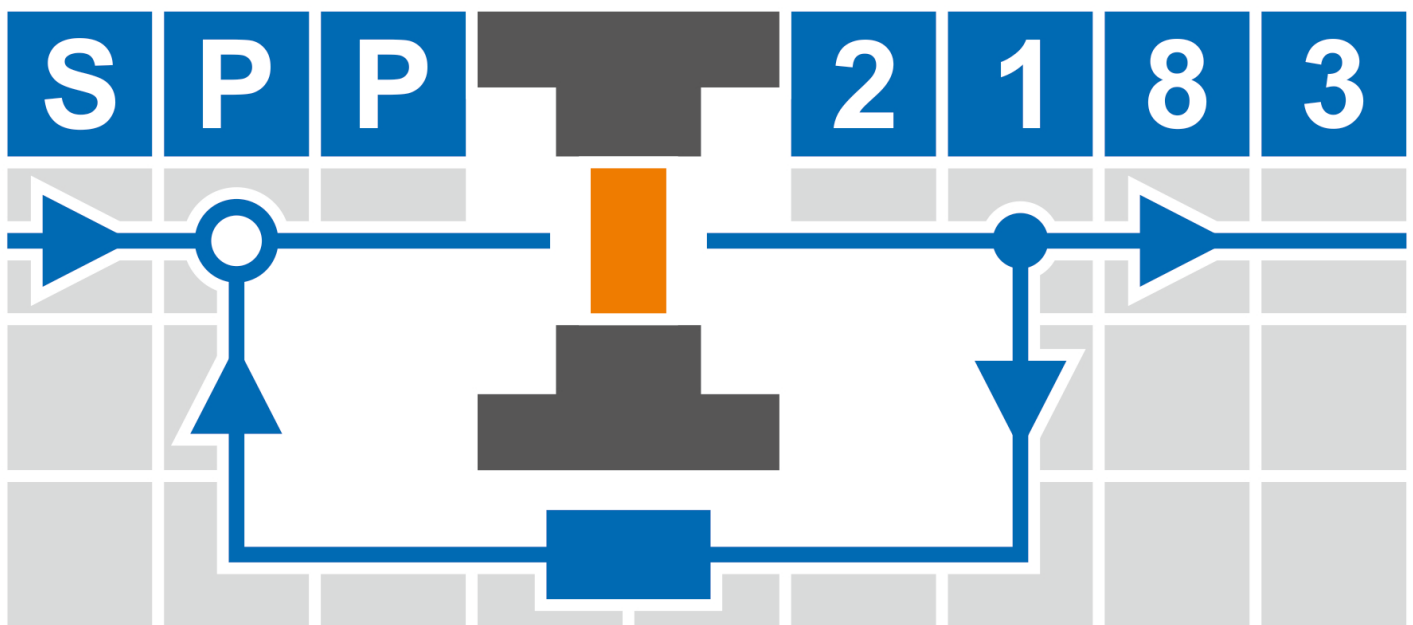


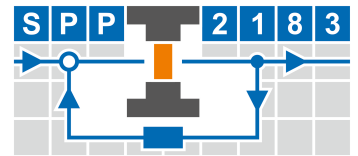


PROPERTY-CONTROLLED METAL FORMING PROCESSES



DFG PRIORITY PROGRAMME 2183

INTRODUCTION



SCIENTIFIC GOALS

In this priority programme funded by the DFG, the scientific fundamentals of process-integrated property control of forming processes are researched and novel approaches for property-controlled forming will be designed and validated.

Due to the current developments in production technology, the property control of forming processes is to be regarded as an emerging field. The cooperation with control engineering provides the opportunity for forming technology to design controllable forming systems based on advanced control engineering methods and to devise the sensors and actuators required for property control in the system design. This collaboration is expected to yield fundamental knowledge about the design of resilient, microstructure- and property-controlled forming processes.

PROBLEM STATEMENT

Production technology is currently being transformed by the transition from automated systems to cyber-physical production systems (CPPS), whose key feature is the spatial and temporal integration of information and planning systems with production facilities. In the context of the resilient factory of the future, CPPS should enable robust and at the same time adaptable production.

These current requirements affect the entire manufacturing technology and thus also demand new thinking in terms of the design of forming processes. Components that require high reliability and a long service life often need to be manufactured using forming technology. For instance, forged high-performance components form the basis of technical innovations in energy and transport technology. Formed sheet metal components combine lightweight design, crash safety, and recyclability in vehicle construction.

DFG PRIORITY PROGRAMME

In March 2018, the DFG decided to set up a priority programme on "property-controlled forming processes" to research this topic. Currently, nineteen groups from different universities and research centers are working on this topic in eight different projects. The range of forming processes under consideration extends from various rolling processes to hot sheet metal forming, forging, and open-die bending.

This brochure gives you an overview of the individual research projects. You can find further information and an overview of scientific publications on www.spp2183.de or via the QR code.



Prof. Dr.-Ing. Markus Bambach
Coordinator of the SPP2183

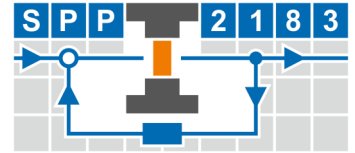


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Funded by
DFG Deutsche
Forschungsgemeinschaft
German Research Foundation

GEPRIS 402694744

Feedback Control of Surface Properties of Flat-rolled Semi-finished Products Based on Online-roughness Measurements of the Strip Surface

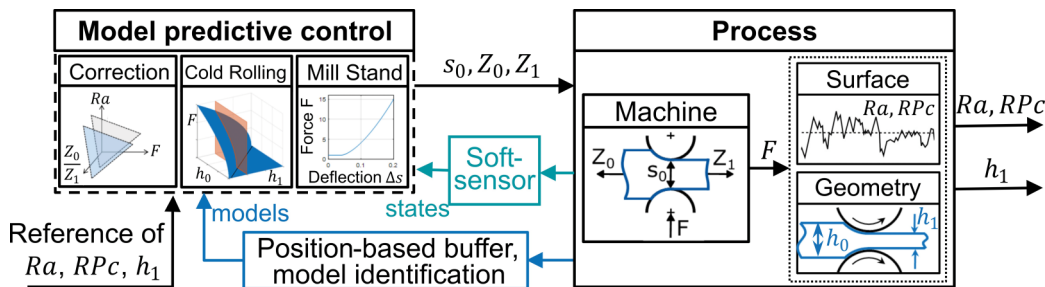


PROJECT

This research project aims to develop a property control system for the skin-pass rolling process based on roughness-measurements of the outgoing strip topography. The surface topography imprinted during skin-pass rolling significantly influences important properties of metallic semi-finished products such as paintability or tribological properties. Today, the skin-pass rolling process is controlled by specifying a rolling force. The latter is calculated in advance using models which describe the surface imprinting of the textured roll. For this purpose, a fast meta-model based on a complex multiscale simulation was derived to describe the roll's imprinting. Additionally, a correction model identifying the roll wear is calculated at runtime.



Prof. Dr.-Ing. Dirk Abel
Prof. Dr.-Ing. Gerhard Hirt



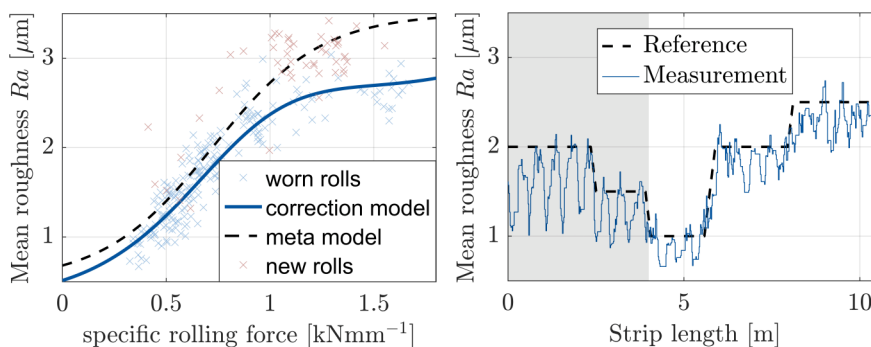
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RESULTS SO FAR

Based on the results of the multi-scale simulation, a semi-analytical meta-model was proposed and implemented into an MPC for roughness control. To identify and compensate the wear of the roll, a data-driven correction model utilizing the online measured roughness of the rolled strip was designed and coupled with the meta-model. In combination with the roll stand and the cold rolling model, which estimate the roll gap of the rolling process, the new MPC system is capable of adjusting the surface topography by varying the strip tension while maintaining a desired final strip thickness. The derived models were tested in an exemplary setup comprising a single roll stand. Furthermore, the manipulation of the strip's mean roughness by a model-based controller was validated for a copper strip of 1.5 mm thickness.



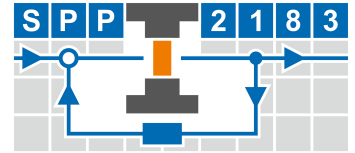
FUTURE TARGETS

In future work, the multi-scale finite-element model will be extended with a more realistic roll profile such that additional roughness metrics (e.g. peak count RPe) can be predicted as well. Furthermore, property models will be derived to describe the relationship between the strip's functional properties and its surface topography. Subsequently, these models will be embedded in an optimization problem whose solution is the optimal reference trajectory of the underlying roughness control. To obtain a robust process control, the controller topology will be augmented to account for model uncertainties stemming from e.g. measurement errors.



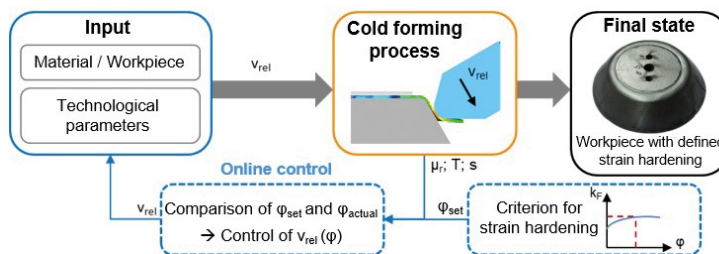
GEPRIS 402694744

Controlled Flow Spinning of Cylindrical Components for Production of Workpieces with a Defined Strain Hardening



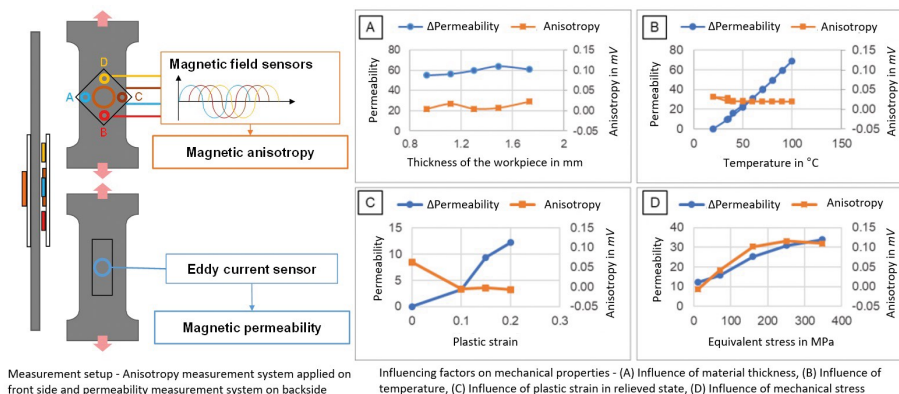
PROJECT

The project aims to control the resulting plastic strain of a workpiece by the production process. For this purpose, a measurement system for plastic strain is developed based on the analysis of the magnetic properties of the workpiece. By a non-contact eddy current multi-sensor system with varied frequencies, the oriented and non-oriented magnetic properties can be separated. The magnetic permeability changes due to the microstructural changes resulting from the forming process, and the anisotropy of the magnetic properties are influenced by residual stresses. The separation of both quantities by a soft sensor enables the targeted control of plastic strain on the component to realize a defined strain hardening.



RESULTS SO FAR

The developed spectral eddy current multi-sensor system allows a measurement of magnetic permeability and anisotropy independent on distance changes and tilting. The measurement of changes of distance was observed as very accurate and a developed calibration procedure reduced the orientation influence on the anisotropy measurement due to production tolerances of the sensor. The experimental results show that the magnetic anisotropy is primarily affected by residual stresses and that the magnetic permeability is affected by both residual stresses and plastic strain. It can be therefore deduced, that the combined analysis of magnetic permeability and anisotropy is necessary for the separation of plastic strain and residual stress. Varying the frequency excitation of the eddy current multi-sensor system allows an analysis of the plastic strain and residual stresses at different depths of the sheet or tube workpiece.



FUTURE TARGETS

Future goals are the analysis and modeling of influencing effects due to the heating of the workpiece, the integration of the multi-sensor system in the process control and the analysis and optimization of the real-time capability of the sensor technology. Furthermore, a closed-loop control needs to be validated for the manufacturing process with a single convex surface (e. g. flow forming of tubes). It needs to be further developed for two double convex surfaces (e. g. spinning of cylindrical components) in order to fully exploit the developed multi-sensor and the novel control concept in the property controlled incremental forming.



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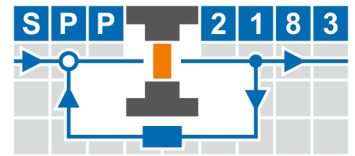
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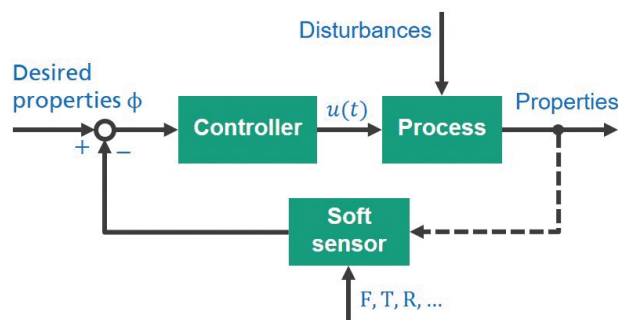
GEPRIS 402694744

Development of a Flexible Isothermal Bar Forging Process for the Property-controlled Manufacturing of Turbine Blades from High-temperature Materials



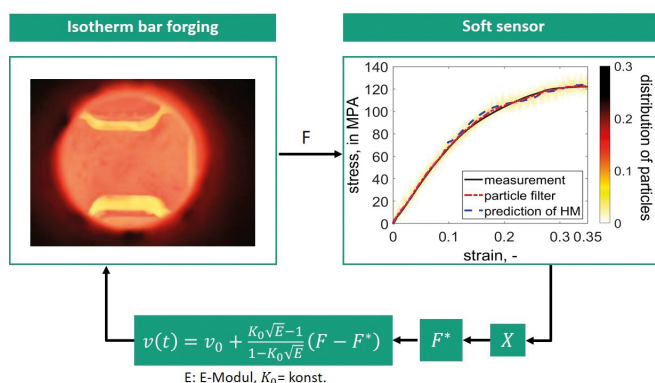
PROJECT

This project aims to develop a property-controlled open-die forging process with local heating. In contrast to closed-die forging, this method enables the control of the property-determining globularization in titanium alloys, which are subject to material- and process-related disturbances. During the forging process, the prediction of average flow stress and the estimation of globularization degree are obtained by the soft sensor system and fed back to the closed-loop controller in order to output high-temperature components such as turbine blades made of titan aluminide. In addition, the results can also be used to other materials and open-die forging processes.



RESULTS SO FAR

In the current phase of the project, a hybrid microstructure and flow stress model composed of a physical model framework and neural networks has been proven to be able to describe the development of microstructure in the workpiece. Furthermore, this model can be adapted online to new measurement data Through the use of particle filters and can thus extrapolate to predict the future microstructure evolution. For adjusting the course of the globularization to the desired target, a new controller including theoretical analysis, stability under uncertainties and convergence orders has already been studied and tested in the forging process.



FUTURE TARGETS

The current research shows the existence and motion of a boundary surface in the workpiece, which separates regions in which the target microstructure is obtained from regions in which this is not the case. Further work will focus on estimating and controlling of the motion of the boundary surface. To achieve this, a new controller will be studied based on the dynamics of the motion of this surface, which is the zero-level set of the microstructure variable to be controlled. Moreover, it is also considered to develop a soft sensor system based on the data-driven prediction, which uses the deviation of the zero-level set from the reference trajectory as a function of the control input and the disturbances. Classification and robustness of controllable microstructure states are also in being researched.



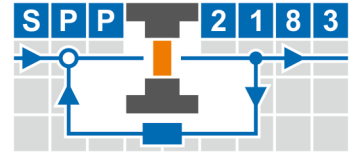
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Thermomechanical Ring Rolling with Predictive Property Control



PROJECT

Tangential Profile Ring Rolling is a highly process for manufacturing ring-shaped parts. By applying specific process parameters with regards to temperature and rate of deformation, it is possible to affect the microstructure, strength and hardness of the final during the rolling process. Different material properties and a large number of interacting material physical effects mean that this is only possible in practice by using a closed-loop control system that is able to adjust the conditions towards a specific goal that can only be evaluated in the future.

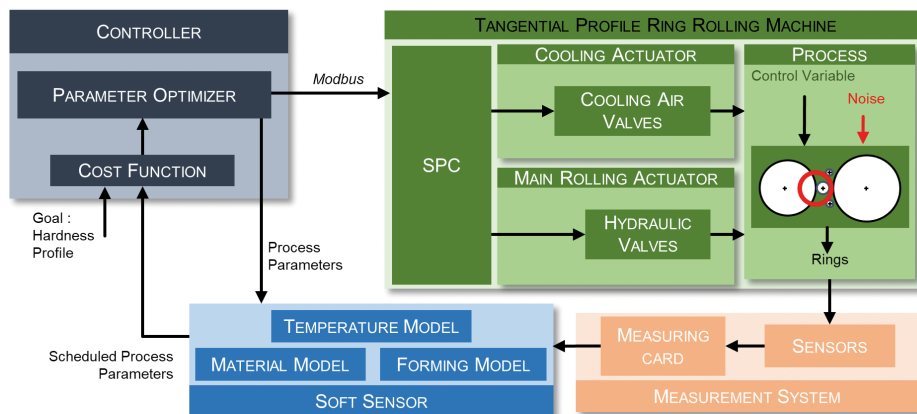


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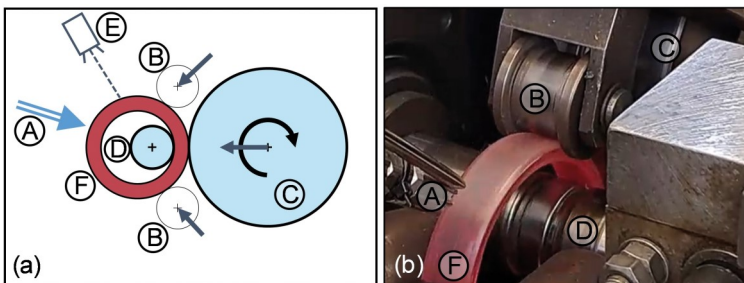
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RESULTS SO FAR

At present, the control requirements of the production machine have been evaluated and the required actors and their effects have been located and soft sensors to observe the microstructure have been developed and tested. It could be shown that depending on the material and process starting conditions, finely controlled temperature and forming profiles can enable localized phase changes similar to tempering or banitization. Additionally, controlled dynamic recrystallization of the material at high temperatures together with work hardening at lower temperatures results in microstructures well-suited for bearing applications. Parameter field process control was developed and a could be proven in a digital twin environment.

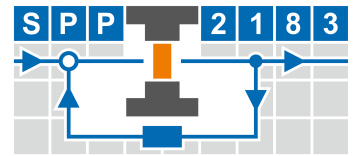


Schematics (a) and photo (b) of the TPRP machine. Legend: A: compressed air outlets, B: guide roll, C: main roll, D: mandrel, E: pyrometer, F: ring, G: stabilization force

FUTURE TARGETS

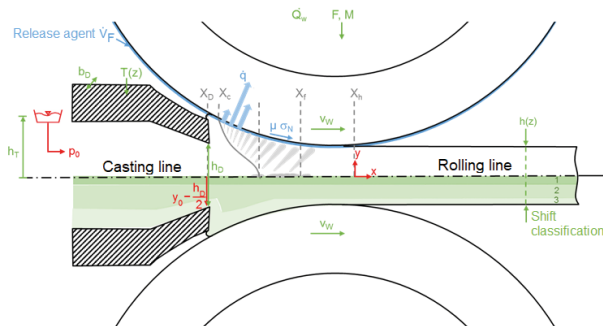
Currently, the digital twin's control system is being implemented as modifications to the production machine. In addition, the soft sensor will also be used for in-process measurement of the material properties that will be used in the control loop. Research into the material effects will extend the capabilities of the system towards materials that have different widely electromagnetic properties in different states. This will also show the magnitude of genuine differences in properties and the uncertainties involved in the system. The influence of these will be investigated with the aim of mitigating or reducing them to achieve a reliable property control system.

Controlled Solid-liquid Transition During Casting Rolling With the Help of Soft Sensors



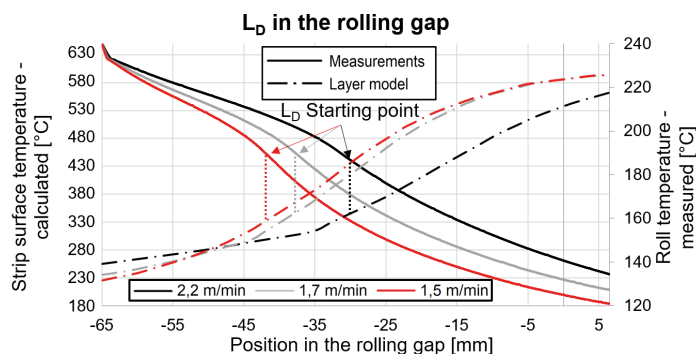
PROJECT

TRC process combines casting and rolling in one process enabling the economical lightweight materials strips production. The microstructural properties of the produced strip are especially influenced by the position of the full solidification point L_D and the resulting plastic deformation. The aim of the project therefore is to control the position of L_D in relation to the desired microstructure of the strip. For this purpose, temperature and pressure sensors are placed in the surface of a roller to detect the solidification front by direct measurements within the roll gap. A new developed digital twin based on a coupled visco-plastic layer model is required to interpret the correlation between sensor data and material properties.



RESULTS SO FAR

The roller was equipped with a piezo sensor, thermocouples and a wireless data transmission. Both calculations on the digital twin and tests have shown that the solidification front could be best influenced by the rolling speed. Experimental data had shown the non-linear relationship between rolling speed, position of solidification front, resulting microstructure and mechanical properties. As the rolling speed decreases, the solidification front moves towards the nozzle and that result in a deformed structure, due to a higher degree of shear deformation. A control concept was drawn up, which contains an observer for the process and a property estimator. Temperature and pressure data were used for improved mushy zone modelling.



FUTURE TARGETS

In the further course of the project, estimators and observers are to be parameterized with the aid of the digital twin. First of all, the control of position and shape of the solidification front is to be modelled and implemented on the system. For dynamic aspects of the automation system it must be determined how many sensors are required to determine the dynamics of the position of a solidification front in relation to the control parameter with a sufficient accuracy. Experimental data will be used to validate and improve the property estimator. Finally, the approach will be generalized, that in the future a control system can be built up only based on the simulated digital twin data.



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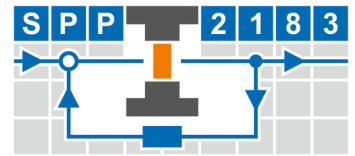
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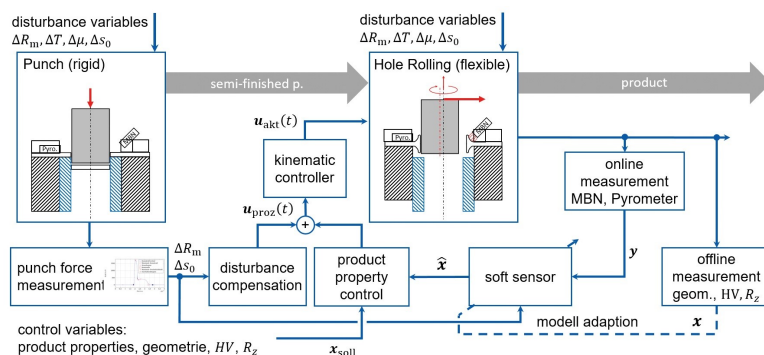
GEPRIS 402694744

Multi-variable Closed-Loop Control with Feedforward Control of Forming Product Properties - Fundamentals and Application to Punch-Hole-Rolling



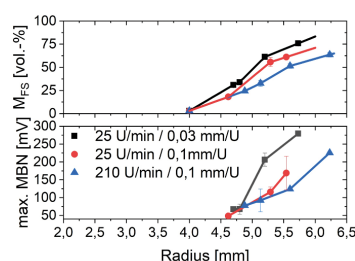
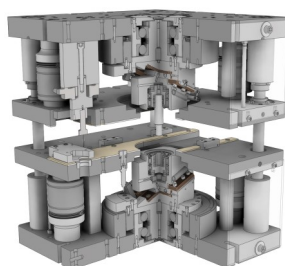
PROJECT

This project investigates the fundamentals of multivariable control of product properties generated by forming processes with feedforward control. For this purpose, a property-controlled, new forming process which is called punch-hole-rolling is developed and a closed-loop control of microstructure, hardness, surface roughness, temperature and geometry is implemented. Inline process information is obtained from Barkhausen noise (MBN) signals, process force and tool position by a soft sensor and fed back to the closed-loop controller. A special feature of the process is the consideration of the semi-finished product information obtained by shear cutting for disturbance compensation in the subsequent process control of the punch-hole-rolling process.



RESULTS SO FAR

In the current research, the controllability of material properties and geometry using the sheet steel DC04 (1.0338) and the stainless steel V2A (1.4301) was investigated and validated during punching-hole-rolling. By using an FE simulation, it was possible to predict the strain rate dependence on the process control variables radial feed rate as well as rotational speed. The influence of the radial process speed on the collar height was demonstrated by investigating a constant expansion ratio. Additionally, the TRIP effect in V2A can be influenced by the radial feed rate and the rotational speed. In combination, this proves the possibility to simultaneously control the product geometry and different product properties. Furthermore, MBN allows a non-destructive characterization of the surface layer state with respect to grain size distribution, martensite content and hardness, which enables a control of the process by means of a soft sensor.



FUTURE TARGETS

Based on the previous investigations, the independent control of the product geometry and different product properties, such as hardness and martensite level, will be realized in an offline control system in the further course of the project. For the measurement of time and location-resolved product properties, order-reduced models will be used as soft sensors. By variation of the shear cutting process, specific disturbance variables are introduced into the process and analyzed for disturbance compensation. Finally, in the next project phase, the disturbance compensation and soft sensors will be validated in an offline control system before focusing on an online product property control system.

PtU FORMING EXCELLENCE

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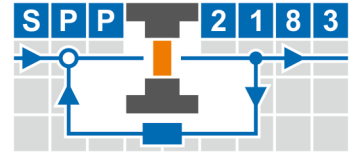
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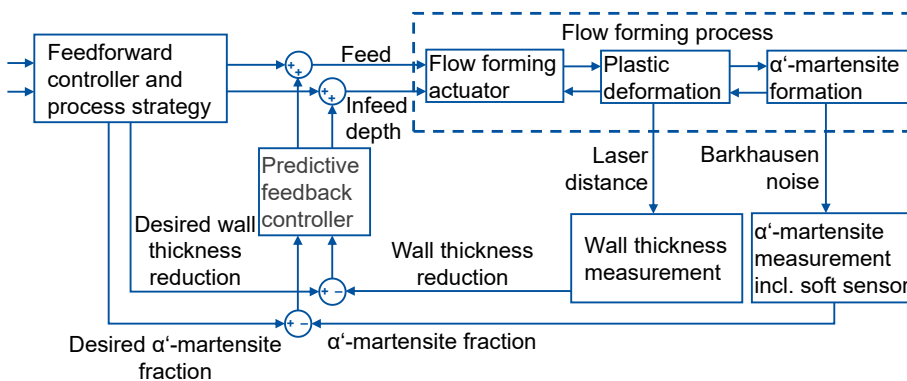
GEPRIS 402694744

Property Control During Spinning of Metastable Austenites



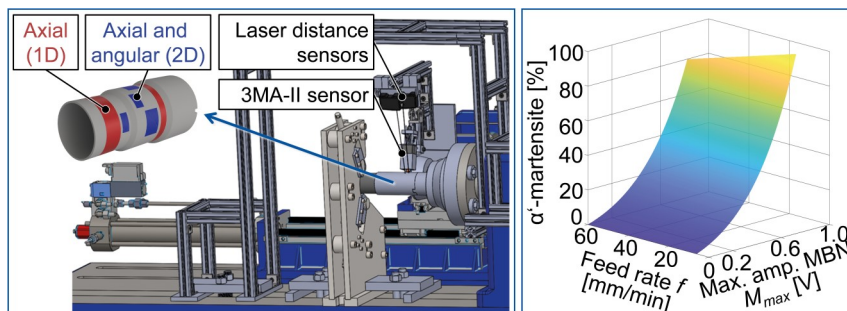
PROJECT

The aim of this research project is a closed-loop control of product properties within spinning processes of metastable austenites. Through a targeted influencing of phase transformation during production, high-performance components are produced, which exhibit defined graded ferromagnetic and mechanical properties (hardness), thus offering added value, e.g. with regard to sensory use. Very high demands are placed on the local resolution of grading, but also on the shape and dimensional accuracy, as well as high productivity, safety and flexibility. The formulation of process-material-property models contribute to the implementation of a soft sensor and a predictive controller for the online closed-loop control of these properties.



RESULTS SO FAR

The focus of the first stage of the project has been the production of axially graded parts using austenitic steel tubes to identify the key parameters influencing the formation of α' -martensite and the wall thickness reduction. The determined correlations between process and properties were mapped in an empirical model. The sensor concept for the online control of properties and wall thickness, consists of a micromagnetic sensor (3MA-II) and laser distance sensors (figure below, left). The micromagnetic measurements are based on the magnetic Barkhausen noise (MBN) principle and were correlated with the α' -martensite content by means of the soft sensor model (figure below, right). A first closed-loop control has been successfully developed for the wall thickness reduction using the online sensors. The influence of the tool geometry and the forming temperature have been investigated, since they are crucial for the production of two-dimensional graded components, which is the focus of the second stage of the project.



FUTURE TARGETS

Future work will focus on the further development of the online closed-loop property control and the investigation of the influence of disturbance variables during production. In addition, the complexity of workpieces will be increased from axially graded structures (1D) into axially and angular graded workpieces (2D).



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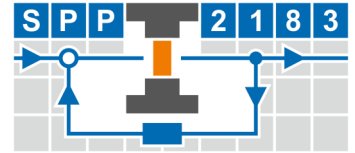
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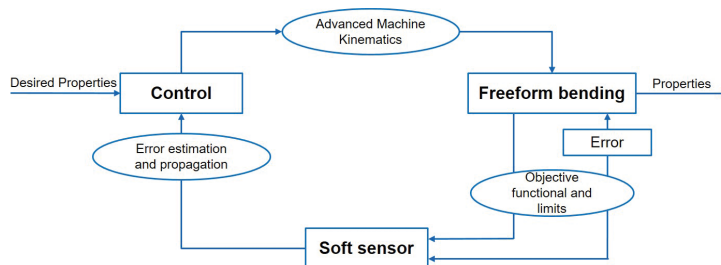
GEPRIS 402694744

Property-controlled Process Design of Freeform Bending Considering Material Properties of the Semi-Finished Product



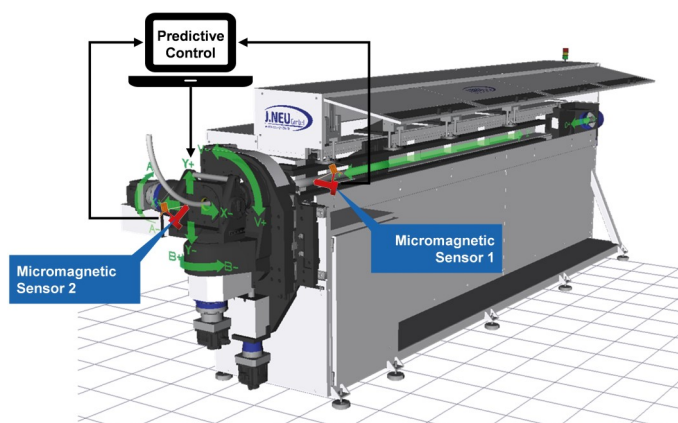
PROJECT

The principal objective of the project is the development and industrial implementation of a property-controlled freeform bending process. In addition to the work piece geometry, it should also be possible to adjust the mechanical properties, such as residual stresses and hardness, during freeform bending. This improved and more comprehensive control increases the quality and efficiency of the freeform bending process. The central innovative idea is the development of a model-based closed-loop control system, based on an inline soft sensor. Thanks to the collaboration of three partners from the fields of materials engineering, control engineering and production engineering, the team is able to successfully achieve the project's goal.



RESULTS SO FAR

In the current phase of the project, the proof of the general property-based control of freeform bending has already been provided. For this purpose, a novel bending strategy of non-tangential bending was developed. This novel approach makes it possible to bend the same geometry with different resulting residual stresses. This leads to a decoupling of geometry and mechanical properties and build the bases for the design of the soft sensor and the control strategy. For the soft sensor it was shown that the properties in the bent component can be determined as well as they can be correlated to non-measurable properties. The results are rounded off by the construction of a first control strategy, which already includes the soft sensor.



FUTURE TARGETS

Further studies need to be conducted on the residual stress state in the bent tube after freeform bending. This will give additional insight on the residual stresses and can ultimately lead to a qualitative as well as quantitative depiction of a formal correlation between residual stresses and hardness. In addition, future work will focus mainly on the further development of the soft sensor and the implementation of the control strategy into the freeform bending machine. The focus will be on the uncertainties that arise in the process as well as in the control or in the soft sensor. In addition, research will continue on the accurate measurement and prediction of the mechanical properties, as well as their influence during freeform bending.



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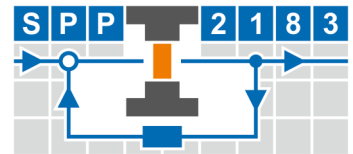
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Product Property Controlled Multi-stage Hot Sheet Metal Forming



PROJECT

Multi-stage hot sheet metal forming enables the production of complex hardened sheet metal components. The product properties result from the forming operations and the simultaneous heat treatment. With the aim to provide the basis for a robust, efficient and versatile production in this project a model- and data-based control of the product properties during multi-stage hot sheet forming will be developed and combined with soft sensors based on process and property models. In the examined demonstrator process (see figure), a 22MnB5 sheet metal blank is first rapidly heated, then formed and quenched. The setting of the product properties takes place within the process control by adjusting the austenitizing parameters and other control variables.



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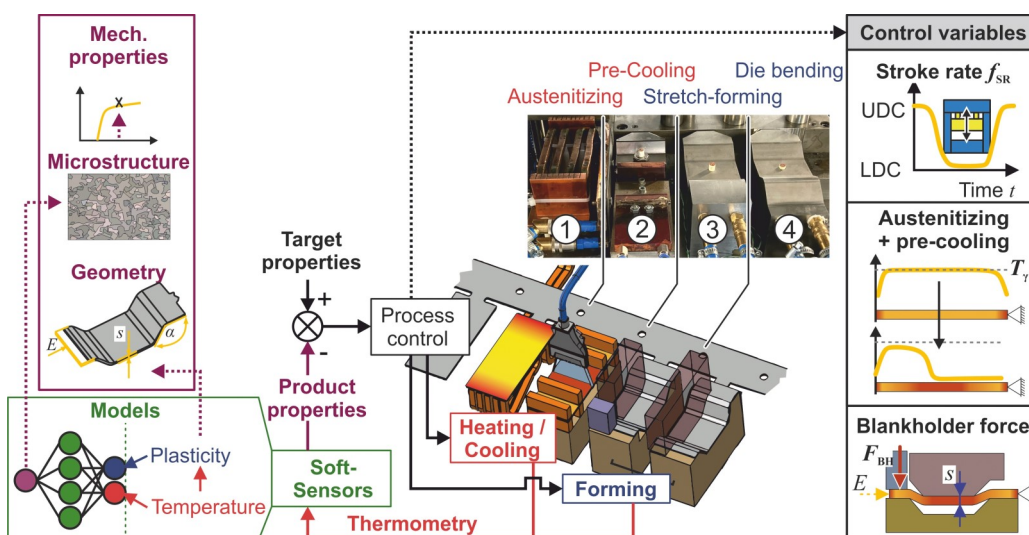


Fig.: Process layout for multi-stage hot sheet metal forming with a closed loop control of product properties in a progressive-die.

RESULTS SO FAR

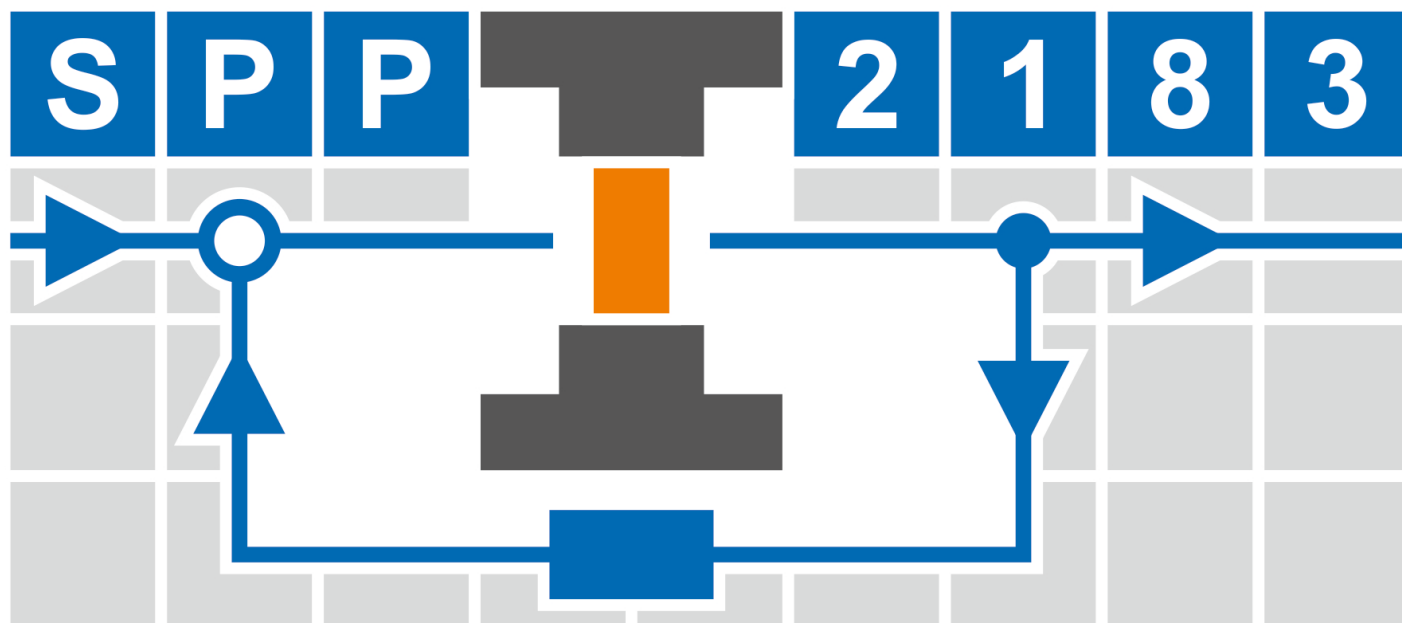
For multi-stage press hardening a control of the product properties is to be established by the feedback of measured variables and their interpretation by so-called soft sensors. So far a temperature soft sensor based on the Dynamic Mode Decomposition (DMD) and its parameter-dependent extension was developed. This can estimate the temperature (distribution) over time at all process-relevant manipulated variables. In addition, an artificial neural network (ANN) based microstructure soft sensor was developed, which predicts the final phase fractions based on plasticity estimation and the output of the presented temperature soft sensor.

FUTURE TARGETS

In the future, the developed soft sensors will be experimentally validated on the presented example process for multi-stage press hardening. Subsequently, a property control will be implemented with the aid of the soft sensors. Besides, the influence of fluctuating coil properties on the product properties will be analyzed using the example of sheet thickness. The aim is to develop a more robust closed-loop process control by considering the fluctuations and reconstructing those using model-based estimation and inversion methods.



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PROPERTY-CONTROLLED METAL FORMING PROCESSES

The research groups of the DFG priority programme have published numerous results in various scientific publications. You can find an overview of these on the website www.spp2183.de or by using the QR Code.

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