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Characterization of Rectangular Copper Wire Forming Properties and Derivation of Control Concepts for the Kinematic Bending of Hairpin Coils

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Abstract

As a result of the continuously growing demand for electric vehicles, innovative production technologies must be developed to fulfill the high automotive requirements for productivity and quality in the manufacturing of electric drives. By providing advantages regarding the degree of automation, the productivity as well as the attainable filling factors in comparison to established round wire winding technologies, the hairpin technology shows a high potential for meeting the requested specifications but also technological weaknesses, especially concerning the process reliability. The referring production process of stators is normally based on the spatial forming of open, hairpin-shaped coils of enameled flat copper wire as well as subsequent joining and contacting processes. Consequently, the hairpin coils represent the elementary components of the process chain and can be either shaped by robust tool-bound or flexible kinematic bending processes that enable the shaping of different contours at moderate tool costs. In this paper, the essential mechanical forming and product properties of flat copper wires with different dimensions and insulation coatings are characterized by means of uniaxial tensile tests as well as metallographic analyses of the material structure, at first. Subsequently, the identified forming properties are correlated to the applied manufacturing processes drawing, rolling as well as continuous extruding and considered as limits of possible material variations. To evaluate the effect of fluctuating wire qualities on the robustness of kinematic hairpin bending processes, the fabrication tolerances are analyzed by finite element simulations, using the example of elementary kinematic bending operations and modeled changes of the material properties. Based on the knowledge of material-based process tolerances, different control concepts for the kinematic bending of hairpin coils are derived and compared based on technical as well as economic aspects.

Keywords: Electric mobility; Stator production; Hairpin technology; Kinematic bending; Closed-loop process control

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1. Introduction and motivation

Mainly driven by a continuously growing demand for local emission-free mobility in general public as well as the ongoing transformation from fossil to renewable energy sources, the market share of electric vehicles is expected to increase by about 20 percent within the next decade [1,2]. The drive train as key component of an all-electric passenger vehicle mainly consists of a high-capacity battery, a cooling system, the power electronics as well as an optional transmission and the efficient electric drive. In order to meet the consumer request for electric mobility, the mass production of traction batteries and electric traction drives must be enabled. For this purpose, new production technologies that provide a high productivity and process reliability at moderate costs need to be developed in a short period of time. Within the scope of electric drives production, the automotive requirements differ from known applications in industry significantly, e.g. regarding the high power density and corresponding necessity of advanced stator winding designs. Consequently, the task of manufacturing a technically demanding product at a maximum degree of

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automation for guaranteeing minimum cycle time and rejection rates, must be rated as main challenge in the production of high-performance stator for electric traction drives at present [3].

One of these production techniques offering a great potential to fulfill the demanding automotive requirements is the hairpin technology. Although the process capability and productivity is already increased compared to classical round wire winding processes by the implementation of more robust shaping and joining processes of bar like rectangular copper wires, the process reliability is still limited due to strong interdependencies within the process steps. [4,5] Therefore, several concepts to increase the robustness of hairpin bending processes by closed-loop control are introduced below, based on a previous analysis of the rectangular copper wire forming properties.

2. Basic principles and research

2.1. Hairpin technology

The hairpin technology is a promising production technique for the manufacturing of stators in large scales at a high quality and low cycle times. The process chain mainly consists of five subsequent steps: shaping (straightening, stripping, cutting and bending of enameled rectangular copper wire), joining (slot lining of stator grooves as well as composing and inserting of hairpin coils), twisting, contacting and insulating. A general overview about the process chain and the sequence of characteristic sub processes is given in the following Fig. 1.

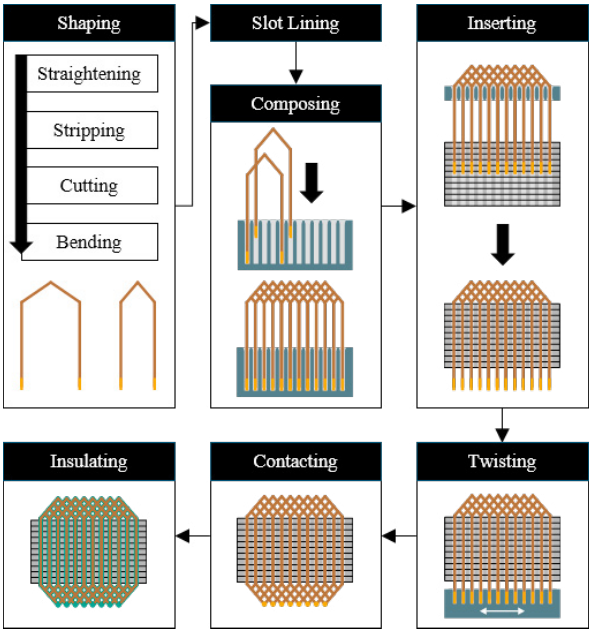


Fig. 1. Process chain for the manufacturing of stators by hairpin technology.

As an initial step of the process chain, the spatial bending of hairpin coils has a significant influence on the downstream manufacturing processes. Because the processes are linked to each other, especially the contour accuracy of the coils after shaping directly affects the reliability of the consecutive composing, inserting, twisting and contacting processes. In contemporary industrial applications, two different approaches are used for the shaping of hairpin coils and need to be differentiated due to a varying sequence of characteristic forming operations: tool-bound and kinematic bending processes (see Table 1) [4].

Table 1. Industrial bending technologies for the shaping of hairpin coils.

	Tool-bound bending	Sequential tool-bound bending	Kinematic bending
Productivity	●	◐	◐
Flexibility	◔ (wire) ◔ (contour)	◐ (wire) ◕ (contour)	○ (wire) ● (contour)
Repeatability	●	◐	◐
Robustness	◕	◐	◔
Tooling costs	○	◔	◕
Machine costs	◐	◔	◔
Load on wire	◔	◐	◕
Restrictions on hairpin contour	◐	◕	●
Application	Standard hairpins	Special hairpins	Special hairpins

●: positive rating; …; ◐: neutral rating; …; ○: negative rating

Providing advantages regarding the cycle time and process reliability but also significant disadvantages in flexibility and load on the insulation coating, tool-bound shaping processes, which usually consist of a planar three-point or rotary draw bending as well as a subsequent spatial die bending, are mainly applied for the production of hairpin contours that are needed in large scales (so-called standard hairpins). Besides, more flexible approaches, which enable the bending of different contours without a change in tooling, are used for the bending of hairpin coils that are needed in smaller batch sizes (so-called special hairpins) to realize the complex pattern of coils given by the electric stator design. According to the current state of the art, both sequential tool-bound processes like rotary draw bending with discrete changes of the bending plane and kinematic bending processes with moving dies are installed in industrial production lines. As already known from the application of flexible bending processes in general, the advantages can be seen in the cost- and time-efficient production of small batch sizes but there are also disadvantages regarding the challenging process control due to complex springback effects and a limited reliability because of low robustness [6].

Because the bending and contacting of hairpin coils are rated as the most decisive steps within the hairpin process chain, there was several research on these processes in recent past. Focusing the shaping of hairpin coils by tool-bound processes and using the examples of three-point and die bending as elementary forming operations, Weigelt et al. showed the potentials of an explicit finite element simulation analysis to deduce process limits and quality characteristics of hairpin coils [7]. Furthermore, Wirth et al. introduced a multi-step simulation model of alternating forming and springback processes based on the explicit and implicit finite element method that enabled the geometric evaluation of a tool-bound hairpin shaping process by covering the whole process chain [8]. An enhanced version of this simulation model was used to analyze the influence of geometric and material wire fluctuations on tool-bound hairpin shaping in [5].

2.2. Manufacturing processes and characteristic properties of rectangular winding wires

Presently, three different types of wire forming processes are used in industry for the manufacturing of enameled rectangular copper wire. The rectangular cross-section of the wire is either be shaped by a classical drawing process, as well-known from the manufacturing of round winding wires, a multi-stage rolling process or continuous extruding by the CONFORM technique [5]. After the forming process an annealing process is carried out in case of drawing and rolling to increase the ductility [9], whereas extruded wires are usually not heat-treated because of the reduced amount of strain hardening whilst forming. Due to the varying process chains, the characteristic mechanical properties of rectangular copper wire must be supposed to be fluctuating over different manufacturers. To limit the variations, technical terms of delivery as well as testing methods for geometric, mechanical, chemical, electrical and thermal wire and insulation properties are described in the series of standards DIN EN 60317 and DIN EN 60851 respectively [10,11].

Within the scope of winding wires, Komodromos et al. published results of several experimental and numerical analyses of round enameled copper wires – as known from classical winding processes – to characterize the forming properties in detail in 2017. Using tensile and compression tests, an influence of the wire diameter on the Young's modulus, yield strength and strain hardening behavior as well as a tension-compression anisotropy were shown. [12]

2.3. Research on closed-loop control for kinematic bending

After the numerical control of forming machines had become industrial importance, several concepts for closed-loop control of planar and spatial kinematic bending processes were published, mainly focusing the shaping of workpieces with big bending radii and cross-sections. An overview about different concepts for closed-loop control of forming processes in general was given by Polyblank et al. & Allwood et al. in [13,14].

In 1982, Hardt et al. presented the first concept for indirect online closed-loop control of kinematic forming processes using the example of three-roll bending and empirical process modeling based on classical control theory [15]. Likewise focusing the three-roll bending of profiles, an indirect online concept for closed-loop control based on semi-analytic process modeling and a PID control element was presented by Yang et al. in 1990 [16].

A first approach for direct offline closed-loop control of multi-axis profile bending was shown by Luo & Joynt et al. [17] in 1996. The architecture used for closed-loop control was derived from a simplified process model based on the analytic bending and twisting theory of elastic-perfectly-plastic beams as well as transfer functions according to classical control theory. In 1997, Sun & Stelson improved the speed of convergence of this control concept by implementing different types of process identification models [18].

In addition, a direct closed-loop control concept for the three-roll bending of profiles based on a semi-analytic process model and tactile curvature measurement after load was shown by Chatti in 1998 [6]. Based on this work, two concepts for the closed-loop control of three-roll profile bending were described by Chatti & Dirksen et al. in 2004. Whereas the first control architecture was based on semi-analytic process modeling, a Fuzzy-control and machine learning methods were proposed in the second approach to increase control dynamics [19]. Furthermore, Dirksen introduced a virtual framework for the numerical simulation of control architectures and implemented a model-based, direct concept for online closed-loop process control using the example of three-roll profile bending in 2008 [20]. Focusing the TSS-bending process, Staupendahl & Chatti et al. pointed a direct and an indirect concept for closed-loop process control in 2016 [21]. Moreover, Katona et al. gave a generic overview about the integration of optical 3-D measurement techniques for direct closed-loop process using the example of pipe bending also in 2016 [22].

A summary of the state of research referring to closed-loop control of kinematic bending processes and the addressed architectures is given in Table 2.

Table 2. Comparison of different approaches for closed-loop control of kinematic bending processes.

Research work	Indirect control	Direct control	Online control	Offline control	
Hardt et al. [15]	●		●		2-D
Yang et al. [16]	●		●		2-D
Luo & Joynt et al. [17]		●		●	3-D
Sun & Stelson [18]		●		●	3-D
Chatti [6]	◐	●	●		2-D
Chatti & Dirksen et al. [19]		●, ◐	●		2-D
Dirksen [20]	◐	●	●		2-D
Staupendahl et al. [21]	◐	◐			3-D
Katona et al. [22]		◐		◐	3-D

◐: design of concepts; ●: implementation of concepts

3. Methodology

To determine the fluctuations of the semifinished material, the material- and geometry-based properties of enameled rectangular copper wires have been analyzed by means of uniaxial tensile tests as well as micrographs at first. Based on the experimental results, the effect of material fluctuations on the contour accuracy of spatially shaped hairpin coils has been estimated by means of a two-step finite element analysis in Abaqus FEA 2019. Afterwards, several control architectures for closed-loop control of kinematic hairpin bending processes are derived to increase the fabrication accuracy and rated based on technical as well as economic criteria.

4. Experimental analysis of wire forming properties

4.1. Experimental set-up and procedure

As introduced in section 2.2, the characteristic geometric and mechanical properties of enameled rectangular copper wires for application in winding processes are defined in the series of standards DIN EN 60317. Because the corresponding testing methods given for mechanical properties in DIN EN 60851 are limited to the determination of single key indices as the tensile strength, the elongation at fracture as well as the springback effect in a special kinematic bending test, the general directives for tensile testing of metallic materials at room temperature according to DIN EN ISO 6892-1 were taken as reference [23].

The analyses were carried out on a tensile test machine of type 2.5kN zwicki RetroLine (ZwickRoell GmbH & Co. KG) and based on the testing method A1 (closed-loop control of elongation speed); the measurement of strain during the tensile tests was realized by means of a tactile clip-on extensometer. As shown in Fig. 2, the dimensions of the tensile specimen were set to 50 mm of measuring length, 70 mm of unclamped length and 170 mm of total length according to appendix C.2 of the standard.

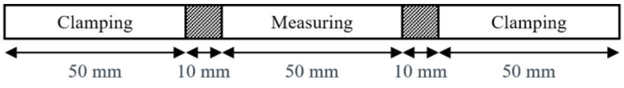


Fig. 2. Dimensions of specimen used in uniaxial tensile tests.

Within the tests, a quasi-static rate of engineering strain $\dot{e}$ of 0.00007 s^{-1} was chosen to determine the Young's modulus and yield strength whereas the flow curves were determined by applying a strain rate of 0.002 s^{-1} as proposed in the standard. To estimate the influence of strain rate on the mechanical properties of the winding wires, a sensitivity analysis was carried out using an up- and downscaling of the strain rate described above by a factor of ten during experimentation ($0.1 \times \dot{e}$ and $10 \times \dot{e}$). For limiting the effect of random variations, a minimum of six specimens was tested for each type of wire at the standard strain rate and a number of three tensile specimens was probed at the manipulated strain rates.

In order to measure the wire cross-sections accurately but also to compare the metallographic microstructure of different batches and types of wire, micrographs were prepared and analyzed microscopically. For this purpose, three pieces of wire were casted with epoxy resin and prepared in a vertical position for the geometric measurements of the axial cross-section whereas the metallographic analysis was based on a longitudinal micrograph of a single wire. Subsequently, the specimens were grinded and polished in a high number of steps to prepare the examination of the cross-sections. Finally, the vertically staged specimens were directly measured microscopically and the longitudinal micrographs were etched before the microstructure was analyzed on a light-optical microscope. An overview about the different types of specimens as well as their characteristic cross-sectional and insulation properties is given in Table 3.

Table 3. Overview of analyzed specimens of rectangular winding wire.

Type of wire	Width	Thickness	Radius	Insulation
Supplier A Batch A	4.15 mm	2.11 mm	0.81 mm	74 µm
Supplier A Batch B	4.17 mm	2.12 mm	0.83 mm	93 µm
Supplier B Type A	4.43 mm	2.72 mm	0.71 mm	290 µm
Supplier B Type B	4.44 mm	2.72 mm	0.70 mm	280 µm
Supplier B Type C	2.30 mm	1.52 mm	0.34 mm	120 µm
Supplier C	4.44 mm	2.73 mm	0.63 mm	217 µm
Supplier D	4.45 mm	2.71 mm	0.72 mm	320 µm

4.2. Analysis of mechanical wire forming properties

Bending processes of metallic materials are significantly influenced by springback effects that occur after unloading as a function of the elastic strain energy stored during the period of forming. Consequently, the amount of elastic springback depends on the correlation of stress and strain, for which reason there is a direct dependency on the material's degree of deformation, yield strength, strain hardening behavior and Young's modulus. [24] Therefore, the characteristic mechanical properties have been analyzed within this work by means of tensile tests at different strain rates.

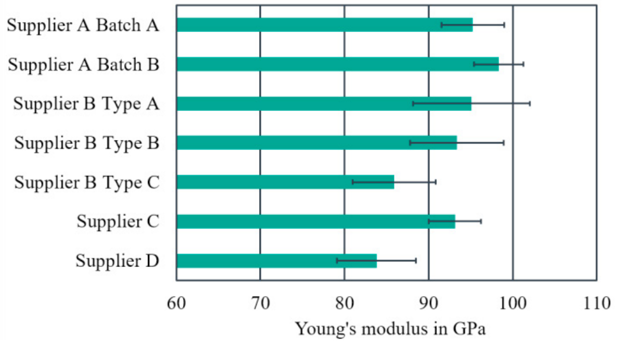


Fig. 3. Young's modulus of different types of rectangular winding wires

As shown in Fig. 3, the Young's modulus of the analyzed types of enameled rectangular winding wires can be quantified to a range of about 84 GPa to 98 GPa. In comparison to the Young's modulus of annealed electrolytic-tough-pitch copper (Cu-ETP), which is specified to be within 110 GPa [24] to 130 GPa [25] in literature, the elasticity is significantly increased. This effect can be mainly explained by the characteristic material properties of the wire insulation that usually consists of polyamide-imide and polyether-imide with a reduced Young's modulus of 4.6 GPa and 3 GPa respectively, according to [26]. Furthermore, the experimental results match the scientific findings conducted by Komodromos et al. on the topic of enameled round winding wires, which have pointed a variation of the Young's modulus in between 99 GPa to 107 GPa depending on the wire diameter and share of insulation in the cross-sectional area [12]. Based on the experimental analyses, a fluctuation of the

Young's modulus of about ± 10 % within different batches and types was identified and taken as boundary condition for the subsequent numerical analysis.

In addition, the influence of different strain rates on the forming properties of enameled rectangular copper wire was analyzed by a systematic up- and downscaling of the applied standard elongation speed $\dot{e}$ by a factor of ten. As shown in Fig. 4, the experiments have pointed a slight dependency of the material's yield strength on the strain rate that corresponds to the correlation given in [25] approximately. Because the effect is small in comparison to the standard deviations of the test series as well as the variations in between different batches and types of the semifinished material, the strain rate sensitivity of the winding wire was rated as negligible within the analyzed range of strain rates.

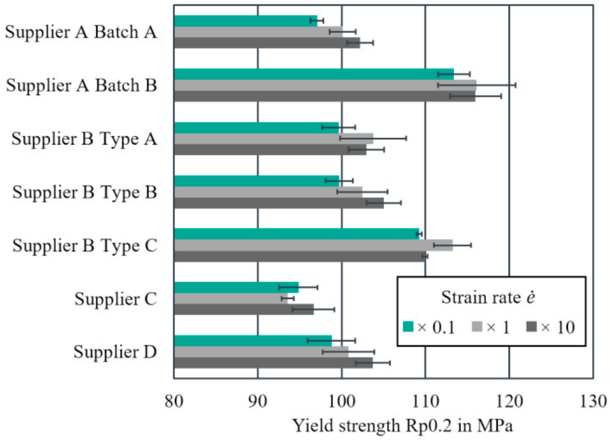


Fig. 4. Technical yield strength $R_{p0.2}$ of different types of enameled rectangular copper wire under variable strain rates of 0.1 × $\dot{e}$, $\dot{e}$ and 10 × $\dot{e}$.

4.3. Analysis of metallographic properties

In order to find dependencies in between the mechanical behavior of the rectangular wire, the process chain of wire manufacturing and the granular structure, several micrographs have been analyzed according to the methodology given before. As noted in section 2.2, the manufacturing of winding wires is highly affected by the forming of the cross-section and a subsequent annealing process.

Within the microscopical evaluation of etched micrographs prepared for all specimen listed in Table 3, no meaningful change in the granular structure of wires provided by the same supplier could be noticed. In contrast, the microstructures of enameled rectangular copper wires manufactured by different suppliers and production technologies have shown a significant variation in the size of grains but no predominant direction of grain orientation. Furthermore, the representative sections visualized in Fig. 5 pointed that the grain size of the rectangular wires manufactured by cold forming processes (drawing and rolling; suppliers B, C & D) and subsequent annealing is much smaller than the grain size of the wires produced by a continuous extruding process (supplier A). Whereas this wide difference can be explained by the variant types of load during forming, the change in granular structure among the cold-formed wires can be probably explained by different annealing and subsequent cooling strategies. In addition, a slight influence of differing cross-sections on the granular copper structure was identified, which correlates to the variation in yield strength within the wire of supplier B. Furthermore, some elongate pores oriented in longitudinal direction can be noticed on the micrographs of all batches of wires provided by supplier A, what might be a result of the manufacturing by CONFORM technique.

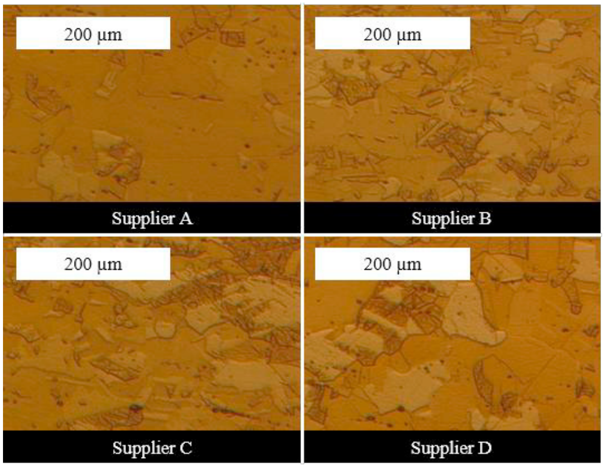
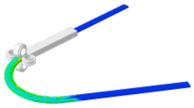
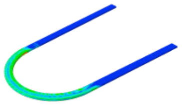


Fig. 5. Etched micrographs of different types of wire in light-optical microscopy using an infrared filter.

5. Numerical analysis on the influence of wire properties on kinematic hairpin shaping processes

As described in detail by Chatti in 1998 [6], the fabrication accuracy of kinematic profile bending processes is significantly affected by the complex springback effect, which depends on geometric and material-based properties of the semifinished profiles. Hence, a fully scripted simulation model of the kinematic hairpin shaping process was implemented in Abaqus FEA 2019 in order to estimate the effect of varying material-based wire properties on the geometry of the hairpin contour.

Table 4. Simulation set-up used for the numerical sensitivity analysis.

	Kinematic 3-D Bending	3-D Springback
Type of solver	Explicit	Implicit
Step time	0.5 s	Static
Elements	49680 elements of type C3D8R (3-D volume elements with reduced integration)	
Process kinematics		

As noted in Table, the 3-D numerical process model consists of two consecutive steps that cover both the forming process and following springback effect by an explicit and a subsequent implicit finite element simulation. Because the numerical results could not be compared with hairpin coils shaped in physical experiments, the model has only been verified by means of geometric and temporal convergence studies, yet. As a results of these preliminary investigations, a total number of about 50 000 reduced-integrated, hexahedral volume elements was used for discretizing the wire and the time step got fixed to 0.5 seconds, what corresponds to a time scaling of about ten. To limit the computational effort and improve the stability of the simulation, the forming tools were modeled as rigid bodies due to the low process forces. For contact modeling, the interaction type "General contact" was applied using a frictional coefficient of 0.05.

After the simulation model was implemented and verified, a numerical study on the effect of variations in material-based wire properties was carried out. Therefore, the Young's modulus and the flow curve were set to three parameter levels based on the results of the previous experimental investigation on variations of rectangular winding wire properties, as shown in Table 5. Within the analyses, an enameled rectangular copper wire of about 6.2 mm × 1.7 mm cross-sectional area including an insulation of grade 2 was assumed. The material properties have been characterized according to the methodology given in section 4.1 at a quasi-static strain rate $\dot{\varepsilon}$ in uniaxial tensile tests.

Table 5. Design of experiments and corresponding parameter levels.

Simulation run	S+	S-	Y+	Y-	S+Y-	S-Y+
Young's modulus	100 %	100 %	110 %	90 %	90 %	110 %
Flow curve	110 %	90 %	100 %	100 %	110 %	90 %

As visualized in Fig. 6, significant deviations of the hairpin contour of about 5.5 mm to 11.5 mm at the open coil ending are already caused by variations of the material-based wire properties of ± 10 %. According to the fundamental bending theory and the correlation of bending torque, Young's modulus and curvature, overbending is induced by a decreased elasticity (Y+) and stiffness (S-), whereas underbending results from the opposite parameter levels.

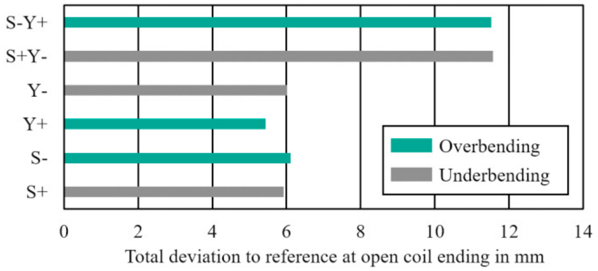


Fig. 6. Spatial deviations of hairpin coils to reference at the open coil ending after variation of material-based wire properties.

Based on the strong variations within the numerical results and a restrictive permissible tolerance of less than 1 mm due to the subsequent process steps, the development of a closed-loop control system is considered as reasonable in order to enable the flexible shaping of hairpin coils by kinematic bending processes without increasing the quality of the incoming winding wire or accepting high reject rates. Consequently, several concepts for direct and indirect closed-loop control of kinematic hairpin shaping processes are proposed and rated below.

6. Derivation and evaluation of control strategies

In the last decades, several concepts for closed-loop control of planar and spatial kinematic bending processes have been presented as described in section 3. According to [13] and [14], two categories of control architectures can be distinguished in general: direct and indirect concepts for closed-loop. Whereas concepts for direct closed-loop process control are generally based on a comparison of actual and desired product parameters without necessity of an additional process model for the transformation of quantities, there is a need for model-based comparison of related process and product parameters to derive a corrective intervention in case of indirect control concepts. Additionally, online and offline concepts for closed-loop control can be differentiated due to the period of time between the occurrence of a measurable error and the correction of the process based on this in relation to the cycle time. Consequently, control architectures that are able to correct an error within the processing of the same part by a process adaption are categorized as online, other concepts, which do not initiate an intervention to the process before the next parts, as offline.

6.1. Direct concepts for closed-loop process control

Referring to the kinematic bending of profiles, direct closed-loop control concepts are mainly controlled by geometric features, e.g. radii or curvatures of the profiles along the arc length. Within the scope of kinematic bending processes of hairpin coils, both an online and offline concept for direct closed-loop control can be deduced.

As pointed in Fig. 7, a direct online control architecture consisting of a simple linear or more complex model-based control algorithm, a process model for the compensation of springback as well as an optical sensor system for spatial measurement of the hairpin contour within the bending process can be applied for closed-loop control of kinematic hairpin bending processes. Furthermore, the same type of control architecture can be used for sequential tool-bound bending of hairpin coils but only requires a planar measurement due to the differing bending kinematics.

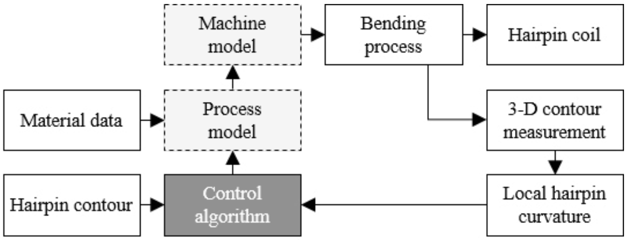


Fig. 7. Concept for direct online closed-loop process control.

Besides, an offline concept for cyclic or run-by-run closed-loop control can be implemented in order to increase the contour accuracy. This architecture, shown in Fig. 8, is also based on the spatial measurement of hairpin contours as well as a control algorithm and process model for springback control. In comparison to direct online process control concepts, the requirements on the processing speed are significantly reduced by the cyclic feedback of information, which results in the applicability of less complex sensor systems and the possibility for implementing more complex process models to increase control accuracy. However the solely cyclic measurement of quality information comes along with a reduced speed of convergence of the contour control system in general, because a corrective control intervention can only be executed over a series of some hairpin coils.

A special case of offline closed-loop control concepts is represented by so-called run-by-run architectures, which enable the reduction of the time interval between two control interventions to the inherent minimum of two consecutive hairpin coils.

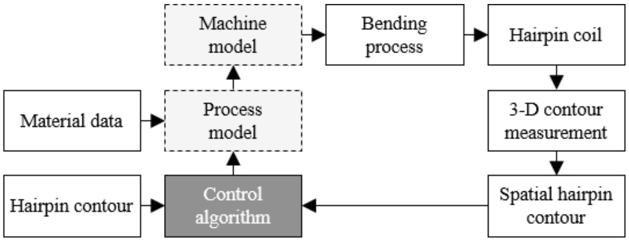


Fig. 8. Concept for direct offline closed-loop process control.

6.2. Indirect concepts for closed-loop process control

In contrast to the geometry-focused approaches of direct control architectures, indirect concepts for closed-loop control of bending processes are frequently based on the measurement and control of process parameters such as forces and torques. Because contemporary machines applied for bending of hairpin contours are mostly automated by electromechanical actuators, which already enable force and torque measurement by internal sensors, the costs and effort for implementing indirect control concepts can be generally rated as low in comparison to direct process control systems.

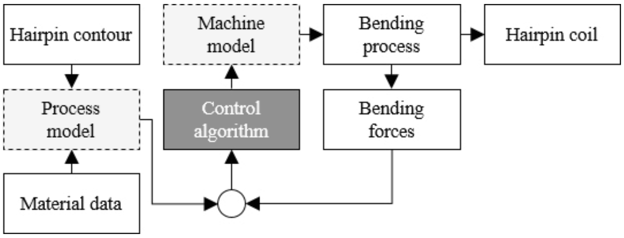


Fig. 9. Concept for indirect online closed-loop process control.

As visualized in Fig. 9 and Fig. 10, there is always a necessity of process models within the architecture of indirect concepts for closed-loop control in order to transform the measured process parameters to the desired product characteristics. Furthermore, both concepts generally consist of an integrated measurement of bending forces during the process that is directly or cyclically taken as data base for corrective interventions to the process by the classical or model-based control algorithm. However, a significant difference in between the online and offline indirect control architecture can be located in the limited time of calculation that can be accepted for process modeling in case of online closed-loop control concepts due to short cycle times, which does not allow the implementation of more complex process models, e.g. based on the finite element method.

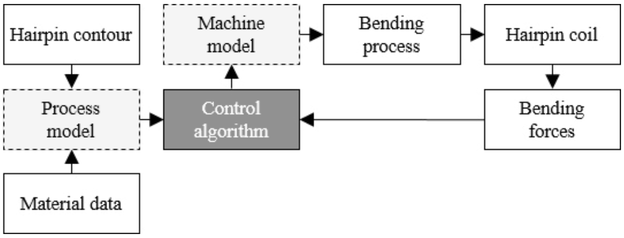


Fig. 10. Concept for indirect offline closed-loop process control.

6.3. Evaluation of closed-loop control concepts

To derive the most potential architecture for closed-loop control of kinematic hairpin bending processes, the concepts proposed before are rated by both technical (accuracy, speed of convergence and stability of control system) and economic aspects (influence on cycle time, implementation effort and costs). A summary of the evaluation is given in Table 6 and explained afterwards.

Table 6. Comparison of different architectures for the closed-loop control of kinematic bending processes.

Control concept	Accura -cy	Speed	Stabili- ty	Cycle- time	Effort	Costs
Direct, online	◕	●	◐	○	○	○
Direct, run-by-run	●	◐	◕	●	◔	◔
Direct, offline	●	○	◕	●	◔	◔
Indirect, online	◔	●	○	◐	◐	◕
Indirect, offline	◔	○	◔	●	◐	◕

●: positive rating; …; ◐: neutral rating; …; ○: negative rating

Due to the advanced technical requirements for spatial measurement of hairpin contours, the costs as well as the effort of implementation must be seen as main disadvantages and challenges of direct control concepts. In contrast, the high control accuracy that can be realized by this type of closed-loop control architecture is rated as a significant advantage in general. In contrast to this, the low costs of implementation can be considered as an advantage of indirect control concepts due to reduced technical requirements on the sensor system, whereas the accuracy of control is always limited to the precision of the mandatory process model used for transforming measured parameters into required quality characteristics as a matter of principle. Considering the influence of the control architecture on the cycle time of hairpin shaping, the maximum process speed of online controlled systems is limited by vibrations of the rectangular winding wire during bending, which would interfere the measurements, as well as the computational effort for modeling and parameter adaption, whereas the minimum cycle-time is not directly affected by offline control concepts.

Because the architecture is a good compromise of technical and economic criteria, direct run-by-run (offline) closed-loop control concepts offer the highest potential for application within the scope of kinematic bending processes for the production of stators by hairpin technology at present.

7. Summary and outlook

In this paper, an experimental analysis of the characteristic properties of enameled rectangular copper wires for use in winding processes was conducted. By means of tensile as well as metallographic analyses, significant differences among the quality of winding wires manufactured by different suppliers and technologies could be identified. As the influence of fluctuations in material-based wire properties was rated as critical for the reliability of the hairpin process chain based on a numerical sensitivity study, several concepts for direct and indirect as well as online and offline closed-loop control have been proposed and compared with respect to technical and economic criteria. Based on this rating, several concepts for direct closed-loop control of hairpin bending processes are focused in actual research work in order to decrease the reject rate in the production of stators by hairpin technology.

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