Innovative self-learning disturbance compensation for straightening processes

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Keywords: Mechatronic Straightening Machine, Self-Learning Disturbance Compensation, Punch-Bending Process

Abstract. To increase the sustainability of forming processes such as punch bending, homogenization of the processed semi-finished product is an essential step in the manufacturing process. High-strength wire materials are usually available as strip material before being further processed in a forming process. For storage and transport, the material is coiled onto coils and transported to the customer. During the coiling process, residual stresses and plastic deformation are introduced into the wire. Thus, the final product quality is also influenced by the geometry of the coil. Straightening machines are used in production lines to compensate for these. Once a straightening machine has been set up, the settings for the roll positions are usually not changed. As a result, there is no reaction to material fluctuations, which means that the components to be produced do not meet the dimensional accuracy requirements. This leads to an increase in the rejection rate in manufacturing processes. To reduce the rejection rate, it is necessary to enable dynamic and flexible infeed of the straightening rollers. In this context, an innovative control concept with disturbance compensation was developed for the straightening process. The disturbance compensation uses a disturbance model that predicts the change in bending curvature over the coil radius. With this prediction, the straightening machine can be adjusted specifically. The roller positions are adjusted by a subordinate position control. The additional feedback from measured geometric product properties from the following punching-bending process enables the straightening machine to be adjusted even in the case of unforeseen fluctuations in the material properties. In this way, it is possible to react to any material fluctuations as required. This novel, demand-oriented adjustment of the straightening machine is expected to result in a high increase in the efficiency of the production process and a reduction of the rejection rate.

Introduction

Semi-finished products made of high-strength flat wire are usually transported to the customer on coils and further processed in downstream processes such as punch-bending. Transport and storage on coils induce pre-curvatures and residual stresses in the semi-finished product, which fluctuate over the coil length during uncoiling. These fluctuations in the semi-finished product have a negative effect on component quality in the downstream processes. In order to compensate for the variable curvature of the incoming straightening material, straightening machines with a large number of straightening rolls are used [1].

To reduce the number of straightening rollers, the fluctuations of the material properties must be known, which is generally not the case. The fluctuations can only be identified with great effort and at the earliest in the straightening result [2]. In addition, online correction of the roller positions in the straightening process is necessary. The rollers of the currently used straightening machines are adjusted manually or by motor. After the initial positioning, however, the rollers usually remain in the same position during the entire production process for a coil. To keep the straightening result constant under these conditions, it is not possible to reduce the number of straightening rollers. With a high number of straightening rollers, the number of alternate bending operations and the accumulated deformation of the material due to the straightening process increase. This leads to a reduction in the strength properties of the material like yield strength, tensile strength, and elongation at fracture [3].

This paper presents an innovative straightening process in which the straightening roller positions are adjusted online. For this purpose, deterministic disturbance variables in the straightening process are estimated. During the straightening process, the straightening result is evaluated based on measurement data and, if necessary, adjustments of the roll positions are derived. The use of intelligent straightening processes offers great potential for making manufacturing processes more sustainable and resource-saving.

State of the Art

In recent years, several approaches have already been investigated to determine the appropriate roller setting for the straightening process. These approaches can be divided into two categories: These are, on the one hand, the numerical approaches, which use FE models to simulatively determine the roller settings. On the other hand, experimental approaches are investigated with the use of different measurement methods.

The numerical approaches are based on FE simulations and often require a high computational effort. An example of this is the work in [4, 5]. The aim is pursued to reduce the residual stresses in the straightened material. The used optimization algorithms rely on a high number of simulations. In [6], an approach is presented in which the settings of all bending triangles in a FE model are adjusted via a sub-routine. Here, the focus was placed on the analysis of the bending line in the straightening machine.

To reduce the simulation effort, a control loop was implemented in an FE simulation in [7]. Within the FE model, the position of the upper edge of the sheet metal at the end of the straightening process was used as the measured variable for determining the residual curvature. The position specification of the second last roller is used as the control variable.

This approach is also used in [2], where a concept for the automated adjustment of a five-roller straightening machine is presented. Based on a force measurement during the closing of the first bending triangle, the material parameters necessary to determine the roller positions are identified. Through a previously conducted simulative parameter study, the appropriate roller positions are known for a variety of different straightening material properties.

This work is continued in [8]. The main difference to [2] is its online capability. This makes it possible to detect changes in the yield strength and pre-curvature of the metal sheet and readjust the roller position accordingly. The disadvantage of these approaches is always a high simulation effort, and the data is only valid for one specific machine configuration.

In addition to numerical approaches, experimental approaches should also be mentioned. In [9], a way to set up a straightening machine for flat wire is presented. Via an offline curvature measurement, the pre-curvature is automatically detected, and possible roller configurations are suggested to the operator via an experimentally created database. A concept for controlling straightening machines during operation is developed in [10]. In order to adjust the position of the rollers, the curvature of the sheet metal is measured behind the straightening machine by distance sensors. An experimental validation of the concept was not carried out. Another concept for an online control is presented in [11]. In this work, the straightening rolls are also adjusted by a control algorithm based on a curvature measurement behind the straightening machine. The residual curvature is continuously determined with a specially developed curvature sensor. However, according to the authors, the curvature measurement is the weak point and does not provide reliable results because the curvature is overlaid by other process forces. Another online approach is presented in [12]. Here, mechanical material properties of the material under study are estimated. However, straightened material is assumed for the estimation.

An approach to control a leveling process based on the magnetic properties is presented in [13]. The magnetic properties are investigated considering the Barkhausen effect in connection with the residual stresses present in the material. The authors noted that with this type of measurement, the residual stress distribution is not sufficiently accurate, so no implementation of the concept was made. In [14, 15 and 16] an innovative setup of a straightening system is presented, which has an eddy current measurement system. Its measurement results can be correlated to variable material properties.

As a conclusion of this chapter, on the one hand the listed works require either a high simulation effort or preliminary tests with a special test configuration of straightening machine and semi-finished product. On the other hand, the detection of state variables of the semi-finished product is not sufficiently robust to implement a dynamic roller adjustment for a good straightening result. However, these are the requirements for a robust and efficient straightening process in order to reduce the rejection rate in downstream processes. For the application of a process, a low simulation and parameterization effort as well as an efficient transferability to other wire types is desirable. A control approach should also ensure the adjustment of the straightening rollers in the process to be able to react to fluctuating wire properties. For this purpose, a robust and reliable measurement of state variables of the wire must be ensured. Based on these requirements, the control approach presented in this paper was developed.

System Description and Control Architecture

The dynamic adjustment of the straightening rollers during the manufacturing process is desirable in order to be able to react to fluctuating material properties of the semi-finished product. Particular focus is placed on the development of a robust and efficient method that does not require time-consuming or resource-intensive preliminary tests and is suitable for industrial use. To develop such an approach, this paper considers the system shown in Fig. 1

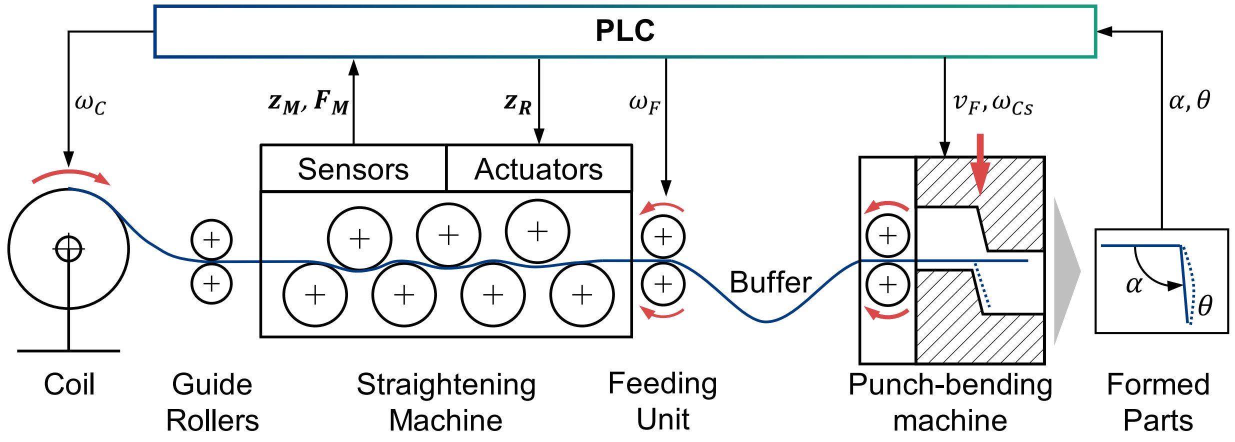

Fig. 1. Schematic representation of the entire manufacturing process.

The semi-finished product is uncoiled from a coil and fed to the straightening process via guide rollers. This is equipped with sensors to determine the roller positions $z_M = \left[z_{1,M}, z_{2,M}, z_{3,M}\right]^T$ and the straightening forces $F_M = \left[F_{1,M}, F_{2,M}, F_{3,M}\right]^T$ on these rollers. The semi-finished product is pulled through the straightening machine by a feeding unit. This is followed by a material buffer to make the transition from the continuous straightening process to the discontinuous punch-bending process. The punch-bending machine has a feeding unit and a punch unit. In this process, an L-shaped component is produced. The bending angle α and the straightness θ of the leg are recorded via a camera. A PLC controls all drives and processes the sensor data. The determining variables for the process speed are the coil speed ω_C upstream of the straightening machine, the feeding speed ω_F of the feeding unit downstream of the straightening machine, the feeding speed v_F at the punch-bending machine, and the cam disk speed ω_{CS} of the punch-bending machine.

The aim of the control approach presented here is the dynamic specification of the reference positions z_R for the straightening rollers. On the one hand, this should keep the quality of the straightening process reproducible at a high level. On the other hand, it should be possible to react to fluctuations in the material properties with a dynamic adjustment of the straightening rollers in the process. The fluctuations in the material properties are interpreted as disturbance variables and can be divided into two categories: deterministic and stochastic disturbance variables. In this approach, the change in pre-curvature over the coil radius is considered as a deterministic disturbance variable. Stochastic disturbances are, for example, width and thickness variations or the material composition.

Accordingly, the developed control approach is also divided into two parts. The feedforward control estimates and compensates for the change in pre-curvature with the aid of disturbance compensation. The feedback control is provided to correct the estimated roller positions in order to react to stochastic disturbances. The structure of the control approach is shown in Fig. 2 and is based on the two-degree-of-freedom structure (cf. [17]).

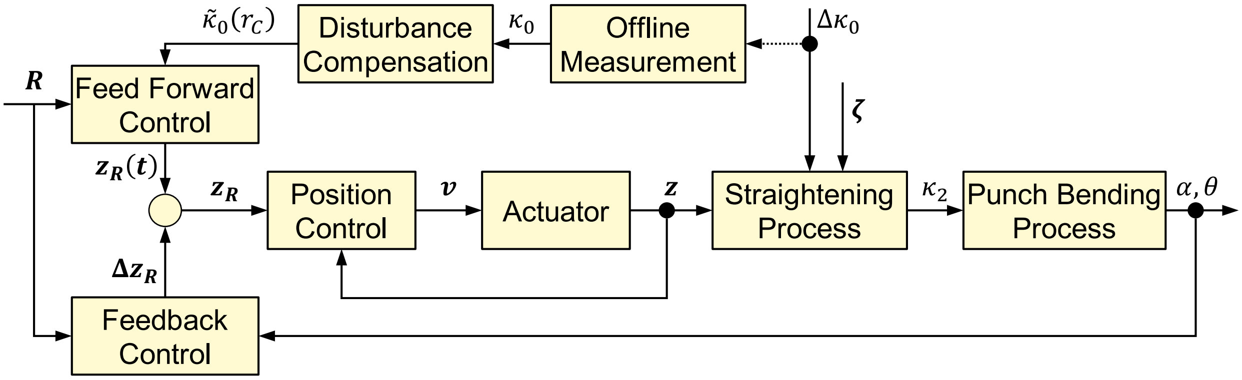

Fig. 2. Scheme of the control structure.

The vector R contains the setpoints for feedforward and feedback control:

$$R = \left[\kappa_{2,R},\ \alpha_R,\ \theta_R\right]^T \tag{1}$$

The variable $\kappa_{2,R}$ describes the reference value for the residual curvature of the flat wire behind the straightening machine. Corresponding, α_R and θ_R are the reference values for the characteristics of the component to be produced. Based on the reference specification, the feedforward control specifies a reference trajectory $z_R(t) = \left[z_{1,R}(t),\ z_{2,R}(t),\ z_{3,R}(t)\right]^T$ for the three movable straightening rollers. This is corrected by the closed loop control during the running process by Δz_R, so that the final reference vector z_R is provided for the subordinate position control of the straightening rollers. These are controlled and act as manipulated variables on the flat wire in the first part of the controlled system, the forming process in the straightening machine. As deterministic disturbance variable, the change of the pre-curvature $\Delta\kappa_0$ influences the straightening process. The totality of all stochastic disturbances is summarized in the vector $\boldsymbol{\zeta}$. This includes, for example, variations in width, thickness, or material composition. With a residual curvature κ_2, the flat wire is fed to the punch-bending process, which represents the second part of the controlled system. In this, an L-shaped component is formed, which is characterized by the quantities α and θ (see Fig. 2). These quantities are measurable and can be fed to the control system as measured values.

The change of the pre-curvature $\Delta\kappa_0$ cannot be measured directly during the running process since it is overlaid by process-related tensile forces. This also applies to the residual curvature κ_2 behind the straightening machine. For this reason, only a measurement of the initial curvature κ_0 before starting the production process when inserting a new coil is possible via offline measurement. The initial curvature is fed to the disturbance model in the disturbance compensation. The disturbance compensation estimates the further variation of the curvature $\tilde{\kappa}_0$ over the coil radius r_C. In the feedforward control, a reference trajectory of the straightening roller positions as a function of time $z_R(t)$ is calculated. The exact operation of the disturbance compensation is presented in the following section. The algorithm of the feedback control is part of future work and will therefore not be considered further in detail.

Disturbance Compensation

After a flat wire has been produced in a rolling mill, it is coiled onto a coil for storage and transport purposes. The deformation of the wire on the coil does not immediately generate plastic deformation. Due to effects such as aging, hardening and also thermal influences a straightened coiled flat wire will again show curvature when it is uncoiled. With the right choice for the position of the straightening rollers, this pre-curvature can be compensated. However, the pre-curvature varies with the radius. The radius decreases continuously with the uncoiling of the flat wire and thus the pre-curvature of the wire increases (see Fig. 3 (a)). This requires a continuous adjustment of the straightening roller positions. To determine the roll positions, the pre-curvature must be known exactly. However, this cannot be measured continuously during the process, as this would require stopping the process and unraveling the wire. Therefore, the goal of the disturbance compensation is to estimate the pre-curvature $\tilde{\kappa}_0$ of the flat wire over the radius r_C.

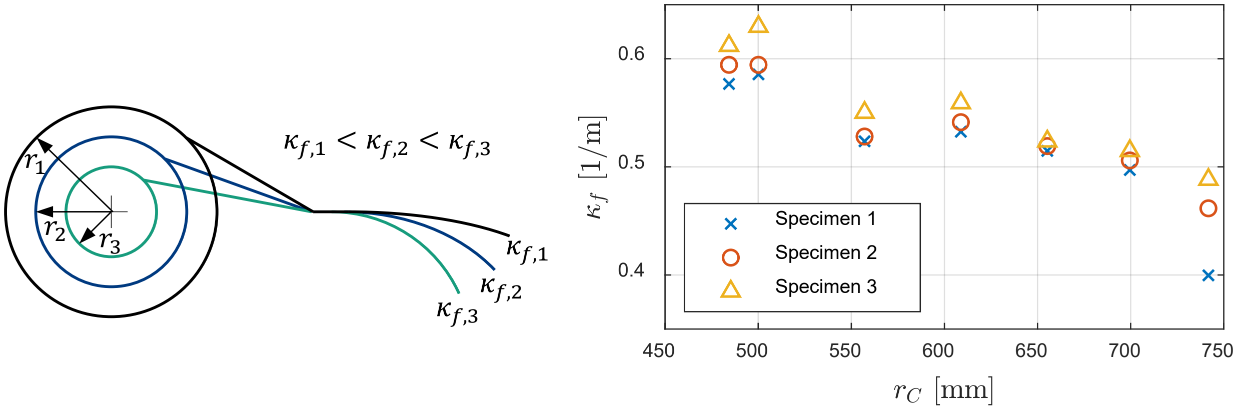

Fig. 3. Trajectory of the pre-curvature over the coil radius: (a) Schematic (left) and (b) measured (right).

Due to the mechanical material properties of steel, the wire springs back when it is uncoiled from the coil. This can be observed especially with wire made of high-strength spring steel. Thus, the curvature κ_f of the wire after uncoiling in the tension-free situation is not identical with the curvature κ_C of the wire in the forced position on the coil. To describe the dimension of this relationship, the springback ratio τ is defined:

$$\tau = \frac{\kappa_f}{\kappa_C} \tag{2}$$

The curvature κ_C during storage can be determined as the reciprocal of r_C. Thus, to calculate the spring-up ratio, it is necessary to measure the curvature of a wire segment in the tension-free state and to determine the coil radius on which the wire segment was stored. The springback ratio is an important parameter for the disturbance model, which will be presented in the following.

The change in pre-curvature during uncoiling a coil can only be measured destructively if specimens are taken from the different coil radii. The result of such an experiment is shown in Fig. 3 (b). The measurement shown was taken on a flat wire (material 1.4310) with a thickness of 0.5 mm and a width of 6.5 mm. The coil had an inner radius of 480 mm and an outer radius of 742 mm.

There is a wide range of factors that influence the trend. Both a fluctuating material composition and cross-section variations as well as the storage time and environmental influences such as temperature and air humidity during storage are to be mentioned here. Added to this are the tension conditions during coiling and the deformation history of the semi-finished product. Other influences such as anelasticity or hardening can be added. All these influencing factors are neither known nor individually measurable by the user who wants to process the semi-finished product into a product. For this reason, the disturbance model is initially kept intentionally simple. A linear relationship between the pre-curvature and the stock radius is assumed. Considering Fig. 3 (b), this is quite reasonable. Thus, the estimate $\tilde{\kappa}_0$ of the curvature over the coil radius r_C can be described with the disturbance model

$$\tilde{\kappa}_0(r_C) = m \cdot r_C + n \tag{3}$$

The parameters m and n describe the gradient and location of the linear function. On the one hand, this approach is particularly robust with respect to the large number of influencing factors and, on the other hand, it is straightforward to parameterize, which is advantageous in view of the limited data available when inserting a new coil. It is necessary to find at least two data points P_o at the outer and P_i at the inner of the coil, which give the information about the pre-curvature value and the corresponding coil radius.

The procedure for determining the two data points is shown in Fig. 4. The inner and outer coil radius $r_{C,i}$ and $r_{C,o}$ are geometrical parameters of the coil and therefore known. For the first data point P_o, the pre-curvature $\kappa_{0,o}$ can be measured using the offline measurement (see Fig. 2) after inserting a new coil. The pre-curvature $\kappa_{0,i}$ for the second data point P_i can only be measured when the coil has been completely uncoiled. Therefore, it is predicted using two sources of information. The first one is the springback ratio from Eq. 2. This can be calculated with the outer data point P_o. Assuming that the springback ratio is approximately constant over the coil radius, Eq. 2 can be transformed to κ_f and the pre-curvature at the coil inside can be predicted. The second source of data is a data base in which the curvature values of the previous coils are stored. Thus, the prediction $\tilde{\kappa}_{0,i,j}$ for the pre-curvature at the coil inside of the j-th coil can be calculated to:

$$\tilde{\kappa}_{0,i,j} = \varepsilon \cdot \tau_j \cdot r_{C,i} + (1-\varepsilon) \cdot K_{0,i} \tag{4}$$

Here, ε indicates how much trust is placed in the estimation via the springback ratio. The value for ε can be set between 0 and 1. The closer ε is to 1, the more confidence is placed in the estimate of the springback ratio. $K_{0,i}$ indicates the moving average of the measured pre-curvature $\kappa_{0,i}$ of the previously processed coils:

$$K_{0,i} = \frac{1}{n}\sum_{k=1}^{n} \kappa_{0,i,(j-k)} \tag{5}$$

In it, n indicates the number of previously processed coils to be considered in the estimation. For the first coil, only the spring-back ratio is available for the estimation.

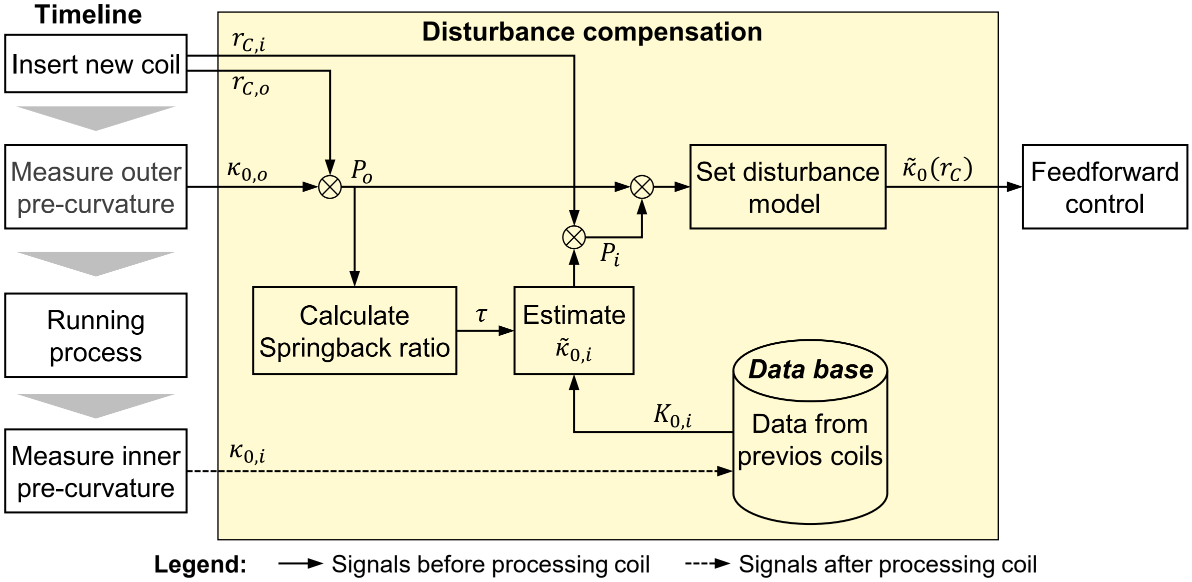

Fig. 4. Working principle of the disturbance compensation algorithm.

In the feedforward control, a nominal trajectory for the straightening rollers can now be determined based on a plant model of the straightening machine, so that the predicted pre-curvature trajectory is compensated over the radius. In combination with the process speed and the coil geometry, the feedforward control specifies a time-based reference trajectory for the positions of the straightening rollers.

This procedure takes into account the properties of the coil to be processed. At the same time, the material behavior on a coil is learned over several coils and the prediction is continuously improved. The more precise the prediction, the higher the straightening quality and the fewer straightening rollers have to be used. Thus, in addition to a high straightening quality, the number of straightening rollers is also reduced and thus the material is straightened more carefully and in line with requirements. As a result, the strength values are maintained and the overbending is reduced.

In order to show how the estimation algorithm works, it was carried out on three samples as an example. A flat wire made of the material 1.4310 and with the dimensions 6.5 mm x 0.5 mm (width and thickness) was considered. The coil had a diameter of 480 mm inside and 742 mm outside. The result is shown in Table 1. The measured pre-curvature $\kappa_{0,o}$ at the outer coil radius and the calculated springback ratio τ are listed in the second and third column. Subsequently, two estimates have been calculated. The first one is the estimate $\tilde{\kappa}_{0,i,1}$ calculated using only the springback ratio. The second estimate $\tilde{\kappa}_{0,i,2}$ was calculated using Eq. 4. For this purpose, $\varepsilon = 0.333$ was chosen. This means that the deflection ratio is trusted to be 33.3 % and the measured values of the previous coils to be 66.7 %. The value was chosen because the estimate about the springback ratio on the first coil was a bit too high. This trend is confirmed on the other two specimens. Thus, for further coils, the trust ratio can be further adjusted in favor of the curvature values of previous coils. In the last column, the measurement of the pre-curvature $\kappa_{0,i}$ at the inner coil radius is shown for comparison.

Table 1. Result of the estimation algorithm ($\tilde{\boldsymbol{\kappa}}_{\mathbf{0},i,\mathbf{1}}$ *corresponds to estimate only based on* $\boldsymbol{\tau}$*;* $\tilde{\boldsymbol{\kappa}}_{\mathbf{0},i,\mathbf{2}}$ *corresponds to the estimation according to equation 4 with* $\boldsymbol{\varepsilon} = \mathbf{0.333}$*).*

#	$\kappa_{0,o}$ [1/m]	τ [-]	$\tilde{\kappa}_{0,i,1}$ [1/m]	$\tilde{\kappa}_{0,i,2}$ [1/m]	$\kappa_{0,i}$ [1/m]
Specimen 1	0.3996	0.2965	0.6177	-	0.5767
Specimen 2	0.4882	0.3622	0.7547	0.6360	0.5944
Specimen 3	0.4617	0.3426	0.7137	0.6282	0.6120

With these calculations, a trajectory for the straightening rollers can now be determined. In the case of specimen 3, the straightening machine would be set for a constant pre-curvature of 0.4882 1/m in a conventional straightening process. With the presented algorithm, a continuous change in pre-curvature from 0.4882 1/m to 0.6282 1/m is considered. This matches the actual change of the pre-curvature to 0.6120 1/m much better than assuming a constant progression. This shows the great advantage of the algorithm. With the estimation of the trajectory of the pre-curvature, the straightening rollers can be continuously adjusted during the running process. The small estimation error is acceptable in any case and is compensated by the feedback control. A static persistence of the straightening rollers in one position over the entire straightening process produces a considerably lower straightening quality and therefore requires a higher number of straightening rollers to compensate for this.

Summary

This paper presents a novel control concept for a manufacturing process consisting of a straightening machine and a punch-bending machine. The concept presented enables the straightening rollers to be readjusted during the manufacturing process. In this way, a novel possibility is created to be able to react to fluctuations in the material properties. Both deterministic and stochastic material fluctuations are addressed. With the help of the learning disturbance compensation, the deterministic change of the pre-curvature over the coil radius is estimated and compensated. Thus, over the entire manufacturing process, the estimation can be continuously improved, and the material behavior learned. Other stochastic material variations can be compensated via online measurement in the punch-bending process.

This method opens up completely new possibilities for an efficient and resource-saving manufacturing process. Compared to conventional levelers, the number of leveling rolls can be reduced. In addition, overbending can be avoided by straightening the semi-finished product as required, which preserves the strength properties of the material. This increases the sustainability of the forming processes in two key aspects: On the one hand, it is possible to react to material fluctuations and adjust the position of the straightening rollers. This leads to a reduction in the rejection rate of the manufacturing process. On the other hand, components can be designed slimmer and lighter by preserving the strength properties of high-strength steels. This results in a high potential for lightweight constructions with high strength steel. The combination of both aspects at the same time in one manufacturing process contributes significantly to a responsible and careful use of resources. At the present time, a potential of up to 8.5% in material savings is estimated. A detailed validation of this control concept is pending in the next research work.

Acknowledgement

The research project IFG 22114 N / P1565 "Development of an innovative straightening machine for three-dimensional straightening and forming" from the Research Association for steel Application (FOSTA), Düsseldorf, is supported by the Federal Ministry of Economic Affairs and Climate Action the German Federation of Industrial Research Associations (AiF) as part of the program for promoting industrial cooperative research (IGF) on the basis of a decision by the German Bundestag. The project is carried out at Fraunhofer IEM.

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