

Innovative Assistance System for Setting up a Mechatronic Straightening Machine

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Abstract. High-strength wire materials are usually available as strip material which is further processed in a forming process (e.g. punch-bending). For storage and transport of the semi-finished wire to the customer, the material is wound onto coils. The manufacturing and coiling process introduces plastic deformations into the wire, which lead to undesirable residual stresses and wire curvature of the semi-finished product. These residual stresses and curvatures cause variations in the material properties of the semi-finished product, which have a negative impact on the subsequent product quality. Straightening machines are used to compensate the residual stresses and the curvature in the wire. At the beginning of the straightening process, the straightening machines must be set up in such a way that residual stresses and curvatures are optimally compensated. This setup process is usually a manual and iterative process, where a lot of material is wasted until the optimal settings for the straightening machine are found.

In order to reduce the amount of material waste, the operator must be supported in the setup process. In this context, a new and innovative setup assistance system was developed to support the operator during the setup process. The setup assistant system automatically detects the wire curvature by means of an optical measuring system. Based on the optically detected measuring points, the wire curvature is determined by a robust calculation algorithm. Based on a database built up through the carried out experimental and numerical research work, the optimum setting parameters for the straightening machine are suggested to the operator without lengthy trial and error. After confirmation by the operator, the roller settings are automatically adjusted by the mechatronic straightening machine. With the presented method, the conventional iterative setup procedure can be made more resource-efficient and a high straightening quality can be reproducibly achieved.

Introduction

High-strength flat wire semi-finished products are usually transported to the customer as coils and further processed in downstream processes such as punch-bending. Transport and storage on coils induce curvature and residual stresses in the semi-finished product. With the aid of straightening machines, flatness errors such as bending or saber curvature but also disadvantageous residual stress states are to be compensated [1]. In straightening processes, the material to be straightened is alternately subjected to low plastic deformation. This plastification ultimately leads to homogenization of the material's residual stresses and the desired flatness [2]. Thus, the quality of the final products to be manufactured depends significantly on the quality of the straightening machines or their adjustment. For straightening high-strength flat wire, the roller straightening process has become established within the wire industry [3]. To compensate for bending curvature, also called longitudinal bend, at least three straightening rolls are required, which are arranged in a so-called bending triangle with respect to each other [4]. In industrial applications, however, the use of the minimum number of three straightening rolls does not show target-oriented results [5]. Especially for compensation of residual stresses more than one straightening triangle is needed. According to [6], at least five straightening rolls are required in industrial practice.

Due to transport and storage on coils, the material properties of the semi-finished product fluctuate over the coil length during unwinding. Up to now, these fluctuations in the properties of the semi-finished product can only be compensated on average, since online measurement of the relevant semi-finished product properties does not yet exist. In order to compensate for variable curvature of the incoming straightening material, straighteners with a large number of straightening rolls are used in the industrial sector [3]. The not fully compensated curvatures and residual stresses in the semi-finished product have negative effects on the downstream processes. Likewise, overly frequent bending tends to degrade material properties, such as yield strength, tensile strength, elongation at break, and deformation capacity, see [6].

For these reasons, the process of setting up a straightening machine is a crucial part of building and commissioning an efficient and economical manufacturing process. In industrial production, the setting of a straightener for the straightening process is initially based on the experience of the machine operator. Since the setup process is very complex due to the many adjustment possibilities, achieving a high straightening quality is difficult to reproduce. With increasing demands on the flatness level of the products, the trial-and-error method as well as the use of experience values from databases prove to be insufficient [7]. In addition, the process becomes uneconomical due to the manual and iterative setup process as well as the waste produced in the process. Step by step, automation strategies and electromotive drives are being integrated into the straightening process (e.g. [8, 9]). Other approaches focus on increasing the modularity of straightening machines in order to be able to respond to changing requirements in manufacturing processes [10]. Currently used straightening machines are set manually or by motor and usually remain in a constant position during the unwinding of a coil. Thus, fluctuating material parameters occurring during the running process have a negative effect on the straightening result [11].

To open up new markets, it is necessary to expand the applicability of flat wire products made from high-strength steel products. This can be achieved by reducing overbending while maintaining homogeneous residual stress curves and straightness of the flat wire. The reduction of the deformation required for the desired straightening result by means of intelligent self-correcting straighteners represents a promising approach to this problem. High-precision and demand-oriented adjustment of the straightener minimizes the stress on the semi-finished steel product during straightening. At the same time, overcompensation due to unnecessary alternating bending processes is thus avoided. The deformation capacity available for the actual production process of high-strength steel materials can be significantly increased in this way. The simultaneous transfer of data acquired during the straightening process, such as the curvature characteristics, to downstream processes and thus the networking of all machines used in the manufacture of the final component leads to an improvement in component quality and a significant increase in the productivity of the manufacturing process. This is because the forming process can be adapted in this way to the remaining forming capacity.

To address these challenges, this paper presents a setup assistance system. This setup assistance system is a supporting tool for the straightening machine operator to automate and make more efficient the process of setting up a mechatronic straightener. Machine setup essentially refers to positioning the adjustable straightening rolls in such a way that the straightening result meets the quality requirements of downstream processes. In a first step, the straightening strategy of the mechatronic straightening process is presented and the role of the setup assistant in it is shown. The structure of the setup assistant is then explained. An important component is the automated curvature measurement, which is described in detail afterwards.

Straightening Strategy

The straightening strategy specifies the mechanisms and rules according to which the mechatronic straightener is controlled and thus the straightening process is monitored and adjusted. The operator must also be involved and constantly supplied with the latest information so that he can intervene

in the process and readjust the machine if necessary. Fig. 1 shows the concept of the mechatronic straightening process. After unwinding from the coil, the semi-finished product is fed through a sensor assembly and then through the straightener. After the straightener, the manufacturing process of the desired product normally follows. If a new coil with different properties is inserted, the straightening process must be set up again. This involves re-setting the positions of the straightening rolls. Usually this is done by an iterative process in which the operator takes material samples, checks them for straightness and then adjusts the settings on the straightener. This process is repeated until the straightening quality is satisfied. The mechatronic straightener presented here has a modular setup assistant that analyzes the semi-finished product properties and accompanies the operator in the setup process. After setup, the continuous straightening process can be started. In this process phase, the process is monitored by means of installed sensor components, which are presented in [12].

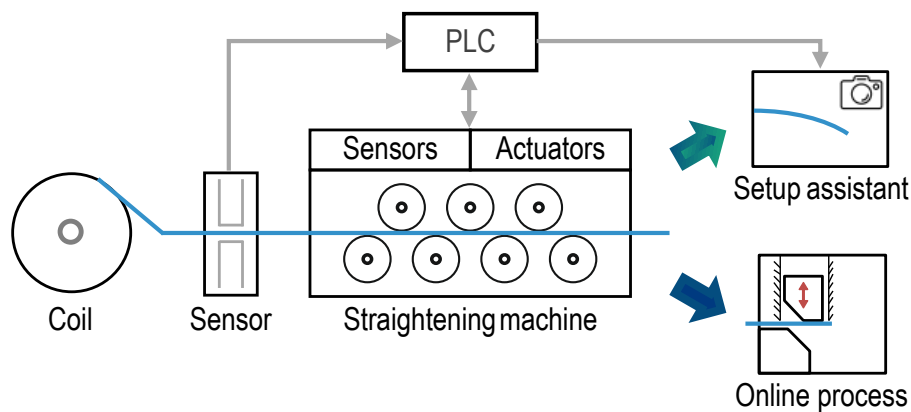


Fig. 1: Conceptual structure of the straightening strategy

The setup process begins with an initial determination of the curvature currently present in the semi-finished product. For this purpose, the curvature parameter B_{Rest} is determined with the aid of optical curvature measurement. This describes the circular segment height over a defined length of a wire section placed free of external forces on a horizontal surface. This characteristic value is used to identify the ideal roll positioning. Based on a hybrid model, a database was generated from which the roller positions for a given B_{Rest} can be derived. These settings are transferred to the straightener and adjusted. The straightening rolls are moved to the corresponding values under position control. Now the straightener is able to produce the desired straightening quality. The setup assistant is to be taken up as a supporting tool. In order to be able to react manually to expected material and process fluctuations, it is possible to correct and adjust the roll positions suggested to the operator. Only after this step is the setup process finally completed and the straightening process ready to start. In addition to the straightening forces and the roll positions, the analysis data of an eddy current measurement are also available to the process control system during the straightening process. Material fluctuations are to be detected via these sensor systems. These are used to monitor the straightening process and, if necessary, signal the need to reset the process.

The mechatronized straightener is intended to enable the advantages of an automated process chain, which promise primarily a reproducible straightening result as well as resource-saving production. The result is an automated straightening process for the production of a curvature-free flat wire geometry, in which the operator is supported by the setup assistant when setting up the straightening rolls. The desired flat wire geometry is produced by the automatic adjustment of the straightening rolls. This also includes the reduction of the number of straightening rolls required for an optimum straightening result. A lower number of alternating bends ensures that a high level of forming capacity is maintained for the subsequent process.

Structure of the Setup Assistant

The setup assistant is a support tool for the straightening machine operator to automate the machine setup process and make it more efficient. Machine setup essentially refers to positioning the adjustable straightening rolls in such a way that the straightening result meets the quality requirements of the downstream processes. Depending on the roller position, the semi-finished product is plastically deformed to a greater or lesser extent and thus straightened. In industrial applications, finding the ideal roll position is usually an iterative process in which the selected settings have to be checked and corrected again and again. The setup assistant supports the operator in this process. The aim of the assistant is to ensure reproducible alignment quality in a linear setup process. The setup assistant essentially consists of three subsystems. These are the automated curvature detection, the database and the graphical user interface. Fig. 2 shows the functional structure of the setup assistant. The upper section shows the operator's view, i.e. the steps to be performed by the operator. The lower section shows the functional structure that works in the background. In the following, the subsystems and their interfaces are examined in more detail.

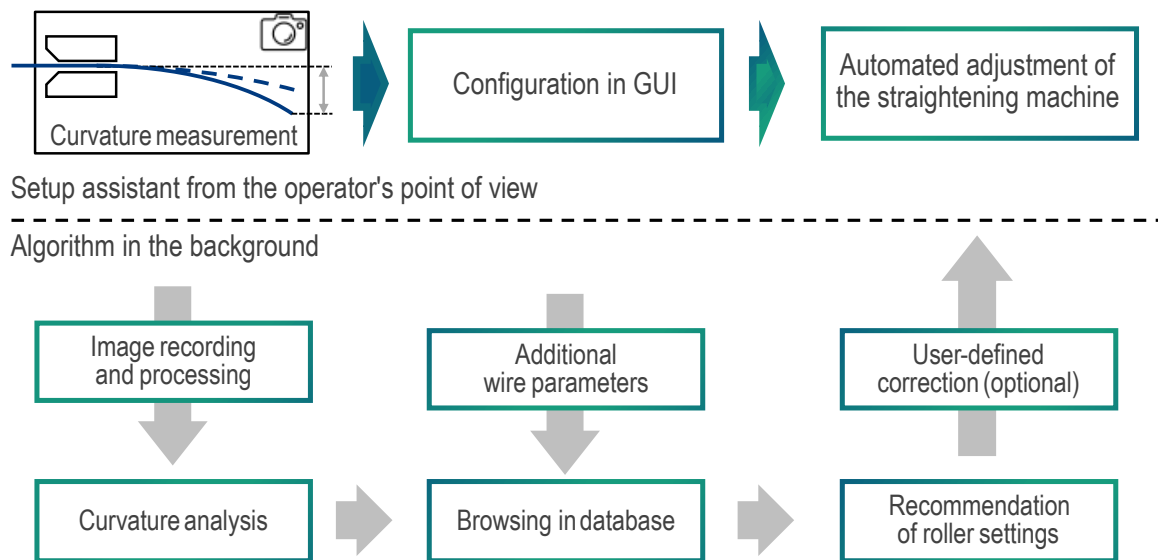


Fig. 2: Schematic structure of the setup assistant

Curvature detection. Curvature detection is used to analyze the current wire condition with a view to the curvature expression. The modular system for camera-based curvature detection can be placed either in front of or behind the straightener. Positioning behind the straightener is advantageous because both the pre-curvature and the residual curvature can be determined here. The pre-curvature is determined during the set-up process when the straightening rolls are not yet in position. Thus, the curvature before and after the straightener is the same. After detection of the pre-curvature, the straightener can be adjusted and the selected settings can be evaluated with the curvature detection. This also allows the operator to readjust the roll settings.

After application of the system on the straightener, the flat wire can be measured. In this case, the defined flat wire length of 180 mm is clamped. In general, it is also possible to design the measuring principle for a different flat wire length. Afterwards, the image can be recorded by the camera and evaluated. The result of the evaluation is the value B_{Rest} , i.e. the curvature still present in the flat wire. This value is the interface to the database and will be included again in the next section.

Database. The database provides the necessary information to determine the positions of the straightening rollers depending on a given curvature value. The curvature value is available after the application of the curvature detection. To build up the database, a detailed series of tests on the roller settings was carried out. The current version of the database has about 3500 records that contain a link between roll positions on the straightener and the corresponding pre- and residual curvature of the specimens.

These relationships were investigated for high-strength steel 1.4310. A complete data set consists of the following six attributes:

- Pre-curvature
- Residual curvature
- Curvature orientation
- Position straightening roller 1
- Position straightening roller 2
- Position straightening roller 3

Graphical user interface. The setup assistant is operated via a graphical user interface (GUI), which is presented in Fig. 3. The GUI is the interface between the curvature detection and the database. It allows easy handling of the setup assistant. On the left side of the GUI the input elements for the parameter settings for the straightening material can be found. There the strip material and its geometry can be selected. For the strip geometry, a selection can be made between flat and round wire, whereby the investigations within the scope of the research project are limited to flat wire.

Afterwards, the operator can choose between concave and convex curvature for the orientation of the flat wire. How the orientations are defined in relation to the straightener is shown on the right side of the GUI. After that follows the selection of the pre-curvature, which the flat wire has. The pre-curvature does not have to be measured manually, as it is common in industrial processes. This is done by optical curvature detection, which has already been mentioned above. In the first expansion stage of the database, a B_{Rest} between 6 mm, 28 mm and 70 mm can be selected. The true curvature value is expected to be between these values. In this case, the curvature closest to the true value must be selected. This selection determines which area of the database will be accessed. The last field is a numeric input field where the desired residual curvature value can be entered.

Setup Assistant

Input

Wire material 1.4310 ▼

Wire geometry Flat wire ▼

Width in mm 3.9

Height in mm 0.4

Diameter in mm 0

Curvature orientation convex ▼

Pre-curvature 28 mm ▼

Residual curvature 0

Determine settings

Output

Pos Roller 1	Pos Roller 2	Pos Roller 3	
2	2	1	<input type="checkbox"/>
3	2	1	<input checked="" type="checkbox"/>
			<input type="checkbox"/>

Straightener ☐ Curvature measurement

Transfer settings to Straightener

Fig. 3: Graphical user interface of the setup assistant

The selection of the settings is completed by pressing the "Determine settings" button. Thereupon, the corresponding combinations of the directional roller positions are displayed in a table on the output page. The table contents are searched from the database and passed to the output area of the GUI. In the output table, a column is assigned to each of the three roller positions. Different combination possibilities are displayed in the rows. They all lead to the same judgement result, as could be shown

in the tests. The table display has the advantage that the user can see the number of all combinations and their parameters at a glance. By selecting a checkbox in the right margin, the line in which the desired roll parameters are listed can be marked. With the "Transfer settings to Straightener" button the selected parameters are transferred to the straightener.

The help window on the output page can be toggled using a switch button below the window. Either the straightener and the active roll for single roll compensation are displayed. Curvature orientation help is also provided in the display so that the operator can distinguish between the concepts of concave and convex curvature. When switching, a definition to the curvature value B_{Rest} is displayed.

Automated Curvature Detection

During the setup process, the curvature of the flat wire is detected at the free end. The shape of the free hanging end is captured with the camera of the setup module and a mathematical equation for the bending line is determined from this. With the help of this bending line, the curvature present in the wire is calculated, taking into account the gravitational force. For this purpose, the wire is clamped on one side in the setup module. Depending on the application, the setup module can be placed in front of or behind the straightening machine. Placement behind the straightener has the advantage that the selected settings of the straightening apparatus can be checked directly. The setup module essentially consists of a camera module, which includes a lens, a backlight LED and a camera controller. After the camera system has been calibrated, the image is captured and evaluated using the camera controller. During the evaluation of the camera image, the previously defined measuring range is divided into areas, the so-called measuring windows (see Fig. 4). In each of these measurement windows, the image evaluation software searches for an object. Due to the backlight LED, the flat wire can be seen very clearly on the image. A piece of the flat wire is detected in each measurement window. For this piece, the centroid of the surface is calculated and output as a pair of values. The division of the measuring area into twelve measuring windows has proven to be sufficient for the setup assistant. Twelve value pairs with x and y coordinates are thus extracted from an image acquisition. After exporting

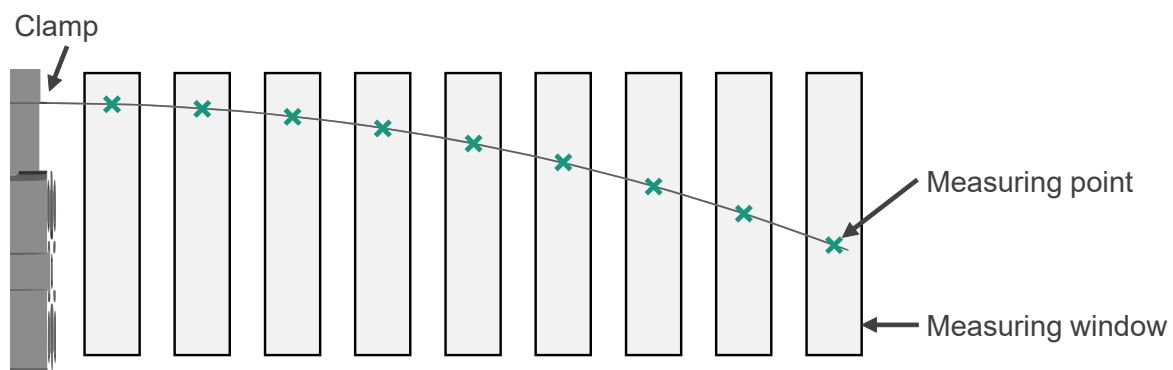


Fig. 4: Setup for optical curvature measurement

the measurement data from the camera controller, two further processing steps must be carried out. These are a coordinate transformation and the elimination of faulty measuring points. In the coordinate transformation, the measurement points are transformed from the coordinate system of the camera K to the coordinate system of the clamp C (see Fig. 5 a). This simplifies the further calculation of the measuring points. In a further step, faulty value pairs are eliminated. Due to unknown interferences it can happen that no measuring point is recognized in one of the defined measuring windows. Thus the interpolation point of this measuring window is specified with the coordinates in the origin. This results in a kink in the detected bending line, which does not correspond to reality. Therefore such measuring errors must be sorted out (see Fig. 5 b). As a result, only 11 measurement points can be used from the previously defined 12 measurement windows. However, since the system of equations

for determining the bending line is overdetermined several times, the loss of one measuring point is compensated for by the other measuring points. The preliminary measurement result is a matrix P_C

$$P_C = [\vec{p}_1 \ \vec{p}_2 \ \dots \ \vec{p}_n]^T = \begin{bmatrix} x_1 & x_2 & \dots & x_n \\ z_1 & z_2 & \dots & z_n \end{bmatrix}^T \quad (1)$$

with n value pairs in the coordinate system of the clamp, which contain the supporting points of the bending line. With the help of the acquired interpolation points P_C from eq. (1) the approximation of the bending line $w(x)$ of the specimen under investigation is performed. A fourth order polynomial is assumed for the approximation of the bending line. The parameters of the polynomial have to be determined on the basis of the metrologically recorded interpolation points P_C . For this purpose, the

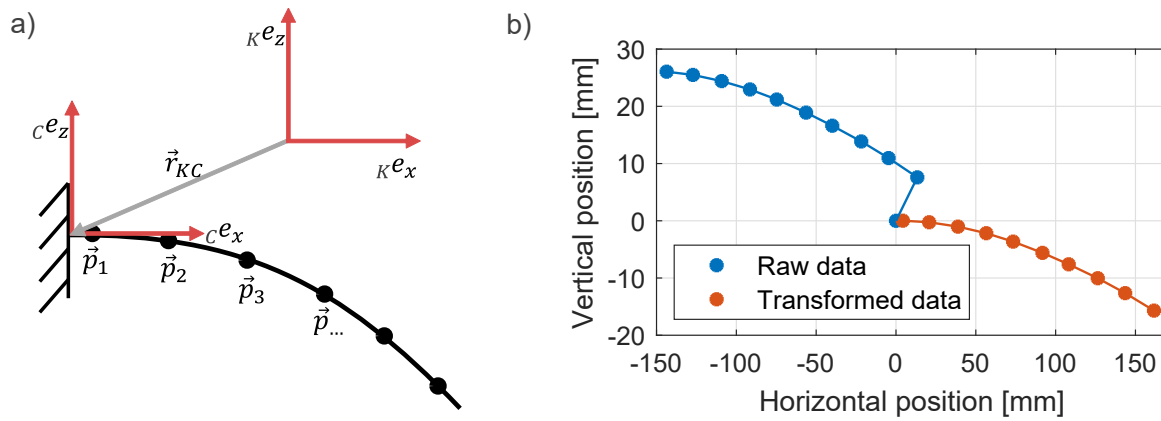


Fig. 5: Processing of measurement data: (a) principle of coordinate transformation; (b) coordinate transformation of a data set with measurement error

Curve Fitting Toolbox in the software *Matlab* is used. The bending line $w(x)$ of a specimen must be calculated to determine the maximum deflection w_{max} at its free end. The last interpolation point of the matrix P_C cannot be used for this purpose, since it does not represent the true end of the wire specimen.

However, to determine the true value of the maximum deflection w_{max} , the approximated bending line $w(x)$ at the location $x = x_{max}$ can be evaluated. Then the relationship

$$w_{max} = w(x_{max}) \quad (2)$$

applies. For the curve length S_w of the approximated bending line $w(x)$ the following applies

$$S_w = \int_{x_1}^{x_2} \sqrt{1 + (w'(x))^2} dx = L_P. \quad (3)$$

Here, the lower limit of the integral $x_1 = 0$, because the clamping of the sample is located in the coordinate origin. The upper limit x_2 corresponds to the searched point x_{max} . The curve length with $S_w = L_P$ and the bending line $w(x)$ are also known. Thus, iteratively a solution for x_{max} can be found, whereby according to eq. (2) also w_{max} is determined. By this procedure, the maximum deflection w_{max} at the flat wire end can be determined from the interpolation points P_C .

The final step is to establish a correlation between the maximum deflection w_{max} and the curvature B_{Rest} present in the flat wire. For this purpose, a series of tests was performed in which specimens with specially set curvature values ranging from $B_{Rest} = 0$ mm to 80 mm were measured. A correlation between the maximum deflection w_{max} and the curvature parameter B_{Rest} was established using these reference points. Fig. 6 shows the reference points as well as the modeled curve. As an approach for the mathematical description a second order polynomial was chosen:

$$B_{Rest}(w_{max}) = a_0 w_{max}^2 + a_1 w_{max} + a_2 \quad \text{mit} \quad a_i \in \mathbb{R} \quad (4)$$

The procedure described in this section makes it possible to measure the optical parameter B_{Rest} for the curvature in a semi-automated way. This does not require cutting out and measuring a single piece of wire, as is the case in industrial practice. The clamping device and the camera system can be placed anywhere in the manufacturing process to determine the flat wire curvature. Together with the described process, this measuring method represents the setup module. With its help, the setup assistant supports the process of setting up the mechatronic straightener.

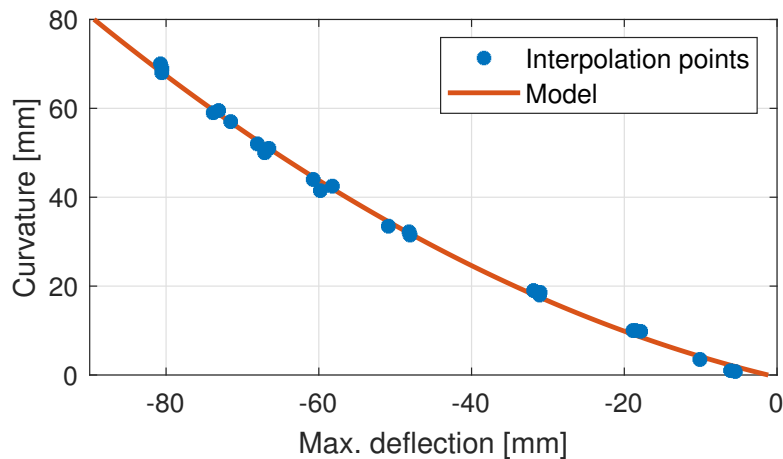


Fig. 6: Modeled relationship of maximum deflection to curvature

Summary

In this paper, a setup assistant system for the mechatronic straightener is presented. With the setup assistant, a supporting tool for the operator of a straightening machine has been developed in order to automate the process of setting up the straightener and to make it more efficient. The setup module detects the curvature present in the material at the free end of the wire. This is done with the aid of optical measuring technology. With the detected curvature, the setup assistant suggests the position of the straightening rolls to the operator, who can then adjust it if necessary. A graphical user interface has been developed for the operation of the setup assistant. Depending on the material, the geometry as well as the curvature orientation and its characteristics, the settings of the straightener for a desired curvature after straightening are displayed. A database is accessed, which provides the settings of the three active straightening rolls depending on the pre-curvature and the curvature orientation. The roller positions of the adjustable straightening rollers are then automatically adjusted. The setup assistant enables an efficient setup process in which a reproducible straightening quality is produced in a linear process. In contrast to the conventional iterative process, the new method requires only a few minutes from the optical recording to the setting of the straightening machine. In this way, the amount of waste produced during the conventional iterative setup process can be reduced immensely. This ensures both cost and time savings as well as more resource-efficient production. Especially in the case of small batch sizes, the waste rate is thus significantly reduced.

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