

An Approach for an Innovative 3D Steel Strip Straightening Machine for Curvature and Saber Compensation

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Abstract. High-strength steel strip materials are usually available as strip material which is further processed in a forming process (e.g. punching-bending). For storage and transport, the material is reeled onto coils and transported to the customer. Due to the residual stresses induced by the coiling process, the subsequent component quality is influenced by the geometry of the coil and changes continuously with the coil radius. In addition, the strip material is subject to saber curvature due to the manufacturing process. Particularly for SMEs, ensuring high component quality with smaller batch sizes is a major challenge from an economic point of view.

To overcome this challenge, variations in the material prior to the forming process must be compensated for with the aid of straighteners. In this project, the overall objective is to develop a novel, innovative straightener that can intelligently compensate for both bending and saber curvature as required. Both flatness errors and residual stresses are undesirable material properties that must be compensated for in the straightening process. In addition, the reciprocal bending stress of the straightening material should be minimized, since otherwise the deformation capacity for the subsequent processes and the strength will decrease. However, these two properties are important quality characteristics.

For this purpose,

- a completely new sensor and 3d actuator concept is going to be developed after a basic investigation.
- Subsequently, a straightening strategy is going to be designed on the basis of previously performed investigations, with the goal that the straightening machine can adapt automatically to the material variations in an optimal way.
- Finally, a new and innovative straightening machine, that will be capable of correcting saber and curvature defects, will be designed, built and validated.

Introduction

Due to increasing globalization and rising quality requirements, the steel and metal processing industry is facing growing cost and innovation pressure. Not least because of their high lightweight potential, high-strength steel materials are meeting the growing material requirements of steel and metal processing in areas such as aerospace and medical technology. In particular, the tight tolerance limits of applicable shape and dimensional accuracies pose a challenge in the processing of high-strength steel strip materials. Improving the processability of high-strength steel materials through the use of straighteners with set-up assistance systems significantly increases the potential for competing with other materials such as aluminum or magnesium alloys.

Semi-finished products like high-strength steel strip materials are generally reeled onto a coil at the end of the manufacturing process. In this form, the material is delivered to the customer, where it is further processed in forming processes such as punch-bending or progressive bending.

Due to the production process of the steel strip and in the course of reeling the steel strip on a coil, a curvature (bending and saber, as shown in Figure 1) of the steel strip occurs and thus undesirable

residual stresses remain in the steel strip. The curvatures and residual stresses introduced into the material in this way lead a) to a significant reduction in the usable forming capacity and b) to increased fluctuations in the properties of the semi-finished products. The saber curvature means that the downstream processes cannot meet the shape and dimensional accuracy requirements, despite the low degree of curvature compared to the bending curvature. As a result, on the one hand a larger quantity of scrap is produced during production, and on the other hand the residual stresses present in the strip material mean that the material-specific forming limit changes are reached earlier.

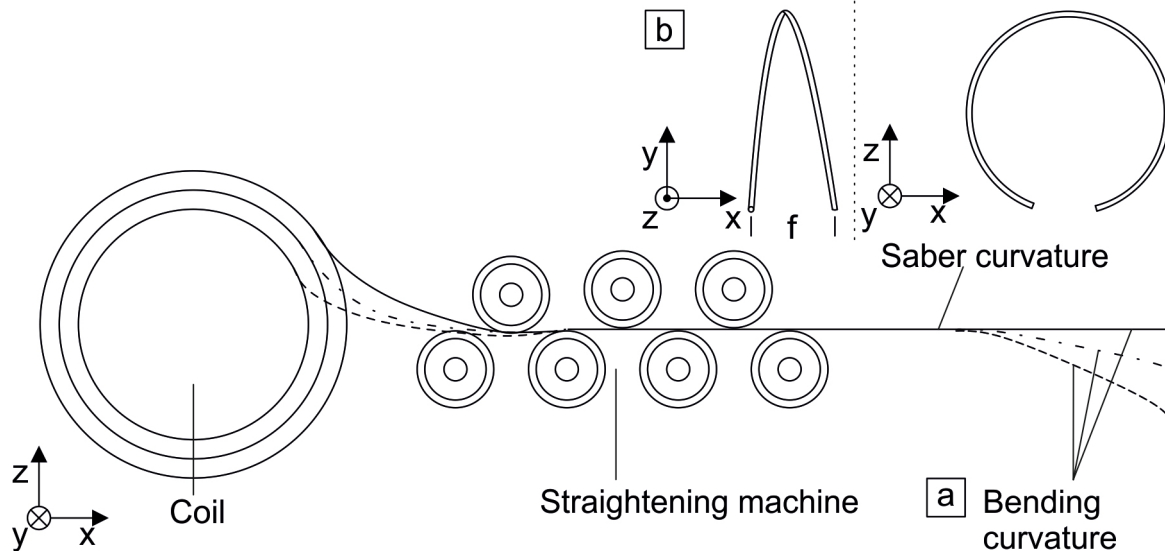


Figure 1: Surface defects of steel strip caused by production and transportation

The low degree of expression of the saber curvature makes its detection very complex and expensive in terms of equipment, since the measurement technology must be carried out with high temporal and spatial resolution. For this reason, saber curvature compensation has not progressed through the market very far, especially since there is also a lack of suitable straightening equipment and straightening strategies. It is common in the industry that after saber curvature is detected, e.g. by one-sided grinding at the infeed of a machine, a coil is complaint and/or returned to the supplier. Consequently, compensation of these geometry errors would lead to increased profitability for the supplier, despite the high cost of recording and eliminating them, since no returns come into the plant. Likewise, the processing plant can process the goods regardless of the delivered geometry quality and there are no production delays.

State of the Art

In accordance with DIN8586, straightening is defined as bending forming in which the emphasis is placed on bringing a workpiece exactly into shape. A characteristic feature of straightening is the alternating change in force or stress during the actual bending operation. In the following, only straightening with longitudinal tension will be considered (roller straightening processes).

Based on the current development work, it can be stated at this point that there are no intelligent straighteners in the field of serial production that can perform 2D or 3D straightening processes depending on the locally varying mechanical and geometric properties of the material to be straightened. There are some straightening machine manufacturers that allow 3D straightening of round steel strip or 90° modular straightening of steel strip. The challenge is that all manual and semi-automated straighteners currently available on the market require in-depth experience of the operator in the field of straightening technology.

In order for the three-dimensional straightening process to deliver a usable result, it is first necessary to identify the flatness errors of the semi-finished product. In addition to the measuring methods for the bending curvature of the semi-finished product, which is shown in a previous work of the authors [1], the detection of the saber curvature has been dealt with in a few publications.

The measurement method using the axial offset of the semi-finished product, as shown in Figure 1, has two disadvantages. First, the steel strip cannot be measured non-destructively, since a single section is required. Second, this measuring method only records the respective section.



Figure 2: Depiction of the effect of multiple changes of the axial displacement over the length of the coil [8]

In Figure 2 is shown that the axial displacement undergoes multiple changes over the length of the steel strip. Systems have already been developed which optically record the saber curvature of rolled sheet [3]. However, this involves a very wide strip in relation to the height. The existing superimposed bending curvature of the steel strip prevents the application of these already developed sensors. Furthermore, a curvature measurement with force sensors has been developed [5]. The prerequisite for this measurement is that the sheet may only be curved in one spatial plane. In addition to the measurement of the material geometry, other sensors and actuators are essential for the straightening process, such as the control of the straightening rolls.

The position of the straightening rolls introduces forces into the material that trigger the desired deformation. Based on these straightening forces, conclusions can be drawn about the process and feedback for control loops can be realized [6].

Force sensors can be used to determine a curvature tendency of the straightened material [4]. With the aid of force measurement, a camber tendency or curvature tendency is determined from the force on a straightening roller or on a downstream guide roller. This is required for influencing the straightening process.

In general, straightening machines can be distinguished between roll position control and roll force control, which are intended to guarantee a constant straightening quality. The roll force control was realized in [6] via a feedback of the qualitative residual curvature via a PI controller, which calculates a target force for an actuated straightening roll. It was hardly possible to stabilize this closed loop control, since the feedback from the semi-finished product to the straightening roller was very high and thus the system tends to oscillate. In contrast to this is the successfully implemented position control, in which a setpoint is specified and this is adjusted via a controller. In this control, the setpoint is specified statically on the basis of simulations carried out in advance, and the "unflatness" of the semi-finished product is compensated by a superimposed control. A considerably reduced but practical variant is presented in [9], in which the position of the straightening rolls can be adjusted to values stored in advance. These stored values can vary depending on the material or semi-finished product, but do not react to parameter fluctuations or disturbances.

As shown, there is a large room and demand for improvements. Below, five specific improvement and development goals are listed.

Action requirement 1: The properties of the semi-finished products vary over the coil length in two directions. The recording of the semi-finished product properties during the process must be ensured so that it is possible to carry out application-specific straightening and to avoid negative effects on the downstream processes. To make this possible, a suitable online measuring technique must be developed.

Action requirement 2: The two-directional straightening process is too complex for a manual setup to be successful. The two-level straightening process must be designed to be automated so that the scrap produced in the process is reduced to a minimum and high setting times are reduced.

Action requirement 3: The flatness errors (saber and bending curvature) vary over the length of the uncoiled steel strip. In most cases, these irregularities even overlap. The straightening process and also the straightening machine must be able to react to these superimposed flatness errors.

Action requirement 4: Existing models for describing the straightening process do not represent the entire tool and machine structure. In addition, the curvature is only recorded after the straightening process, so that rejects can occur because corrective action is only taken after the target deviation has been determined.

Action requirement 5: Due to the use of many reciprocal bending stresses, a tensile-compressive stress occurs in the steel strip. Due to the kinematic hardening behavior (Bauschinger effect) of the steel strip materials used, the deformation capacity of the material used changes unfavorably. Therefore, the straightening process should include a minimum of forming operations.

Strategies to meet the action requirements

Opening up new markets by extending the applicability of flat steel strip products requires an increase in forming capacity. However, this forming capacity is reduced in conventional straightening processes by the large number of forming operations. It is quite common to use up to 13 straightening rolls [7], where three rolls set up a straightening triangle. In each of these triangles, the material is plastically deformed and the usable deformation capacity is reduced by alternating bending operations. A reduced deformation capacity prevents optimum utilization of the semi-finished product in the subsequent production processes. As a result, the efficiency of material utilization is reduced, in some cases considerably.

A promising approach to solving the above-mentioned challenges is the reduction of the deformation required for a good straightening result by means of intelligent self-correcting straightening machines. Self-correction minimizes the load on the semi-finished product during straightening so that the residual stresses locally present in the flat steel strip are compensated as required. At the same time, overcompensation due to unnecessary alternating bending processes is avoided. In addition, the quality of the straightened material is to be considerably improved by compensating not only the bending curvature in the x-z plane (Figure 1) but also the curvature of the x-y plane (saber curvature). Due to the planned continuous adjustment of the straightening modules, any curvature variation in between can also be compensated. This enables application-oriented compensation, since the defects of the semi-finished product are not necessarily limited to the x-y or x-z plane. In this context, a more precise curvature compensation is achieved with only a minimal change in the previously adjusted material properties. The research and development of the novel 3D straightener is based on the fundamentals created in the AiF-funded project "Set-up assistance systems for straighteners" in the form of the developed set-up assistance system [1, 2].

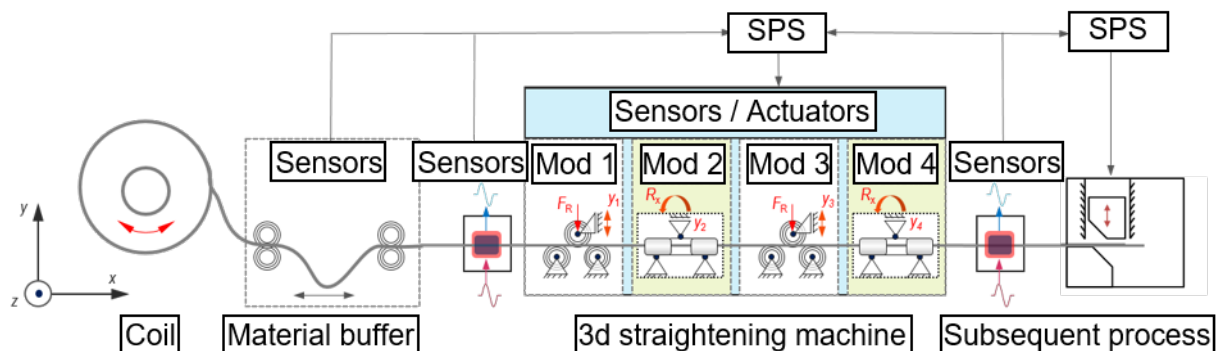


Figure 3: Schematic setup of the 3D steel strip straightening machine

The obtained findings form the basis for the design and development of the sensor and actuator systems as well as the compensation strategy of additional geometric errors such as the saber

curvature or the he-lix shape. The aim is to increase the productivity and manufacturing quality of production processes that process steel strip material made of high-strength steel materials, thus creating new fields of application for the steel material. To achieve this goal, the development of an innovative 3D straightening machine (a schematic is shown in Figure 3). Therefore, three main topics will be pursued in the development:

The first focus is the development of a novel intelligent straightening machine for three-dimensional self-correcting straightening processes. This is realized by an innovative die design in which the straightening modules are rotatably arranged around the steel strip to be straightened (Figure 4). The possibility of controlling the individual straightening modules, their roll infeed and additionally orienting them continuously to one another means that not only bending curvature but also saber curvature and helicoid formation can be counteracted.

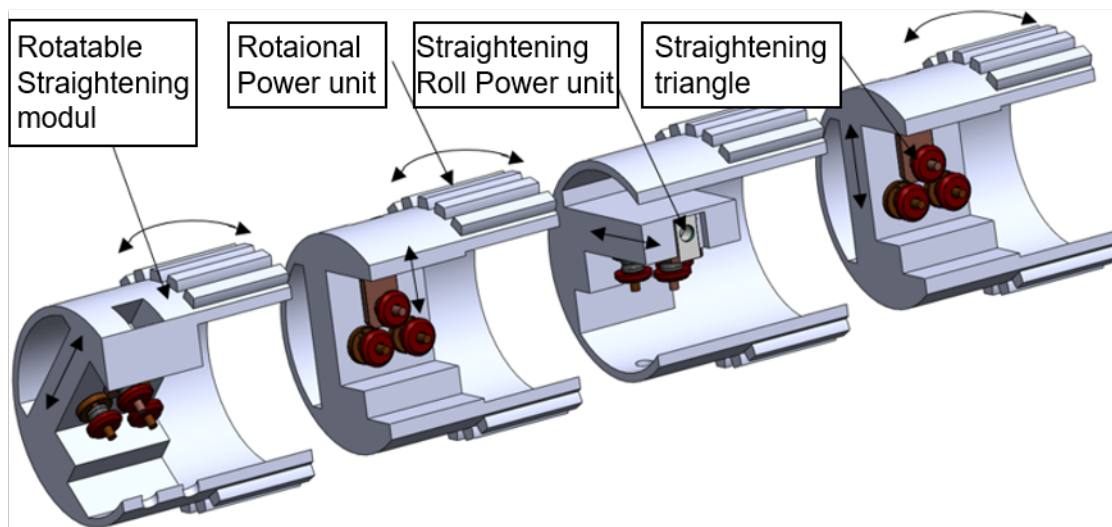


Figure 4:Idea sketch for the construction of a modular 3D straightener

The next focus is the construction of a novel sensor concept. As soon as the straightening process is in productive operation, tensile forces and moments act on the semi-finished product, smoothing out the bending and saber curvature. For this reason, the detection of these curvatures is not possible via optical or tactile sensors. This challenge is to be met by research into novel sensor concepts based on inductive measurement methods. The novel concept should also enable the online acquisition of measurement data during production operation, allowing the steel strip condition as well as flatness errors to be constantly monitored and detected. On the one hand, these data can be used to react to fluctuating input parameters and optimize the straightening process. On the other hand, the use of the data in the sense of Industry 4.0 is also planned, whereby the entire subsequent production process benefits.

A third focus is the automation of the straightening process. This automation concerns both the setup process of the straightening machine and the ongoing operation of the production chain. The conventional manual setup of straighteners in industry results in high reject rates and a less resource-efficient handling of semi-finished products, especially for small batch sizes. The setup of the conventional straightening machine consists of several parameters that need to be adjusted to each other manually. This setup procedure produces scrap which can be saved using an automated 3d straightening machine. Additionally, the straightening result is also strongly dependent on the expert knowledge of the operator, which rarely leads to reproducible results with changing operators. On the one hand, automation of the straightening process reduces the susceptibility to errors and the risk of production downtime. On the other hand, the quality of the straightening result can be reproducibly stabilized at a high level. This implies a reduction of the reject rate in the production chain, which increases the attractiveness of manufacturing products in small batches in particular. The automated

setup of the straightening process and the automated process itself lead to an increased ecological and economical process where resource consumption and monetary commitment are reduced.

By focusing on these three main aspects, a new development of an innovative and flexibly applicable 3D straightener is carried out, which can be used not only for straightening but also for generating a defined curvature of the semi-finished product. This, in combination with the use of asymmetrical (triangular, L, U) profiles or steel strips, opens up new fields of application for the processing of high-strength steel. These include the reinforcement of components by contour-matched steel strip structures (front end), the use of steel strip for power transmission (gear construction) or as spring elements in mechatronics. In addition, the packaging and food industries or plant construction and sorting systems are conceivable areas of application. Due to the automatic and reproducible set-up, even smaller batch sizes can be produced economically.

Summary

In summary, the main objective of this research project is the development of an intelligent straightener that can straighten and form the steel strip in several dimensions individually adapted to the subsequent process. With the aid of several straightening modules, which can be actively revolved around the steel strip, it is possible to compensate not only for the pure bending curvature of the steel strip but also for other flatness errors such as saber curvature. Innovative sensor concepts enable self-correction of the 3D straightener during the running process in order to minimize unnecessary downtimes in production and thus saving resources and money.

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