Modular 3D roller straightening – a new approach to straightening and forming of spring steel wires (X10CrNi18-8)

DAHMS Frederik[1,a *], HOMBERG Werner[1b]

[1] Paderborn University, Forming and Machining Technology, 33098 Paderborn, Germany

[a]fd@luf.upb.de, [b]wh@luf.upb.de

Keywords: Incremental Forming, Straightening, Flat Wire, Spring Steel Wire, Sabre Curvatures

Abstract. Spring steel wires are usually supplied and stored on coils. The manufacturing and coiling processes of these wires induce inhomogeneous plastic deformations that lead to undesirable residual stresses and varying wire curvatures in the semi-finished product. These residual stresses and curvatures defects are causing varying process conditions in the subsequent manufacturing processes, which have a negative impact on the product quality, leading to wastage and thus affecting the economic and ecological efficiency. Especially the curvature deviations must be compensated for the stability of the subsequent processes. This is usually realised with roller straighteners, which are set manually by the machine operators only at the beginning of a process. In this paper, we introduce a new approach with a modular straightening-machine design and a new set-up process. The more isolated deformation behaviour in a module-based straightener overcomes the complexity of interactions between the close-positioned spaced straightening rollers. This is combined with a set-up process that is independent of conventional material testing, modelling the actual and batch-specific behaviour of the wire in the straightening process. The exact knowledge and time-consuming determination of the material properties thus becomes obsolete. The experimental investigations show the influence of defined straightening strategies on the residual stress evolution and the residual forming limit of the spring steel wires (X10CrNi18-8) in the new straightening process.

Introduction

Spring steel wires are usually supplied and stored on coils. The manufacturing and coiling processes of these wires lead to inhomogeneous plastic deformations and friction induced heat that lead to undesirable residual stresses and varying wire curvatures in the semi-finished product [1, 2]. These residual stresses and curvatures defects are causing varying process conditions in the subsequent manufacturing processes, which have a negative impact on the product quality, leading to wastage and failure and thus affecting the economic and ecological efficiency [3]. Especially the curvature deviations must be compensated for the stability of the subsequent manufacturing processes. This is usually realised with roller straighteners (Fig. 1, (a)), which are only set manually by the machine operators at the beginning of a process and are not adjusted during the continuous process. The disadvantages here are the necessary experience of the machine operator, the duration of setting up and the static setting of the rollers that do not respond to the variations in the material properties and curvature in the online process. Therefore, various approaches for the model-based determination of the set-up and control of the straightening-machines have been developed. These include analytical forming models [4, 5], models considering the Bauschinger effect [2, 6], and also FEM [7]. But, all these approaches, of course, require the operator to have a greater understanding of materials science and testing, which increases labour costs and set-up times.

Therefore, the aim of our research project is to enable the development of an automated and online controlled continuous wire straightening process. However, as previously mentioned, setting up, modelling and controlling the straightening process on conventional straightening machines is an enormous challenge due to the complex mechanical interactions between the closely spaced straightening rollers.

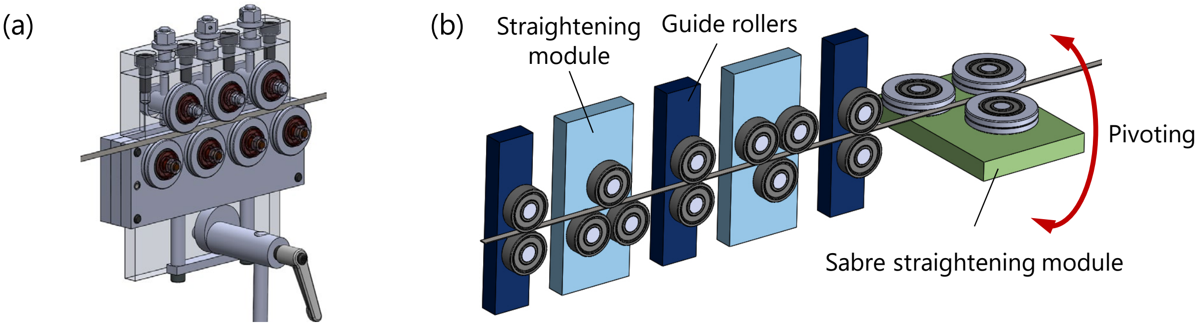
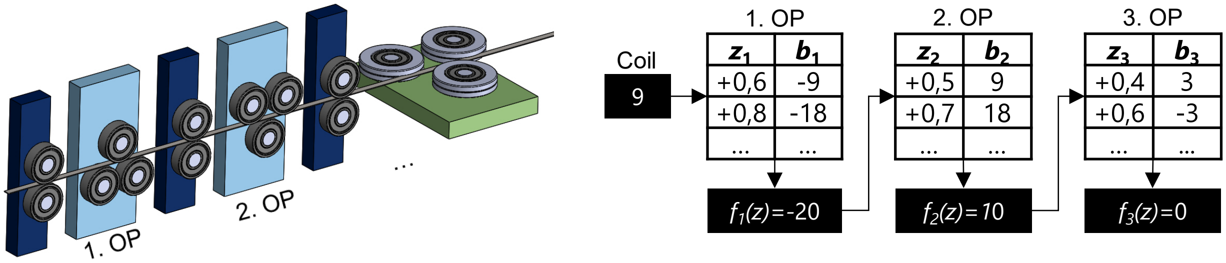


Fig. 1 (a) (Sabre) straightening-machine with conventional design, (b) 3D straightening-machine with modular design.

Therefore, a new approach on straightening with a modular straightening-machine design (cf. Fig. 1, (b)) and a new calibration process is presented (cf. Fig. 2). With a more isolated deformation behaviour in a module-based straightening machine, we will overcome the complexity of the interactions between the close-positioned straightening rollers, enabling a model-based process control. This is combined with a calibration process that is independent of conventional material testing, modelling the actual and batch-specific behaviour of the wire in the straightening process. The exact knowledge and time-consuming determination of the material properties thus becomes obsolete. With this new approach, bending and sabre curvatures and their combined occurrence (helix) are to be compensated but also purposefully formed. The last module, for the straightening of sabre curvature, can also be pivoted to compensate twisting.



1. OP

z_1	b_1
+0,6	-9
+0,8	-18
...	...

$f_1(z)=-20$

2. OP

z_2	b_2
+0,5	9
+0,7	18
...	...

$f_2(z)=10$

3. OP

z_3	b_3
+0,4	3
+0,6	-3
...	...

$f_3(z)=0$

Fig. 2 Concept of the calibration process of the modular straightening machine with exemplary data.

As there are no standardised guidelines on how to set up conventional straightening machines and, of course, the novel modular straightening machine, first a set-up strategy (calibration process) was developed (cf. Fig. 2):

1. Measure the wire's initial curvature *b*, in this case, represented by the vertical height on a defined segment of a circle.
2. Define a straightening strategy, e.g. the desired curvatures *b* after each straightening operation.
3. Cut a set of 250-500 mm long wire segments. At least two per module. More will make it more accurate.
4. Measure the resulting curvature *b* after the first straightening operation in the first module of at least two different roller positions *z*. A starting value for a first positioning of the roller *z* can be calculated using the corresponding strain from a calculated bending curve and the yield strength reported by the supplier or is known from previous calibration processes.

5. The model of the actual and batch-specific behaviour of the wire is built up by least-square regression of the resulting curvatures *b* and the roller positions *z*. These can be linear for simple straightening jobs and quadratic for higher accuracy.
6. Roller position z_1 can now be determined solving the regression model for the curvature value *b* defined in the straightening strategy.
7. Prepare at least two wires (with z_1) for each of the following directional modules for setting them up.
8. The following straightening modules are then set up as described in the previous steps (4-6), whereby the last target value is usually 0.

This process is possible because the design is modular, and therefore, there are no interactions between the modules and their straightening operations. The same set up process is also performed for sabre straightening and forming (cf. Fig. 3 (b)), whereby this process is generally located subsequent (cf. Fig. 1 (b)). The main reason for this layout is that the dominating curvature component is to be straightened first.

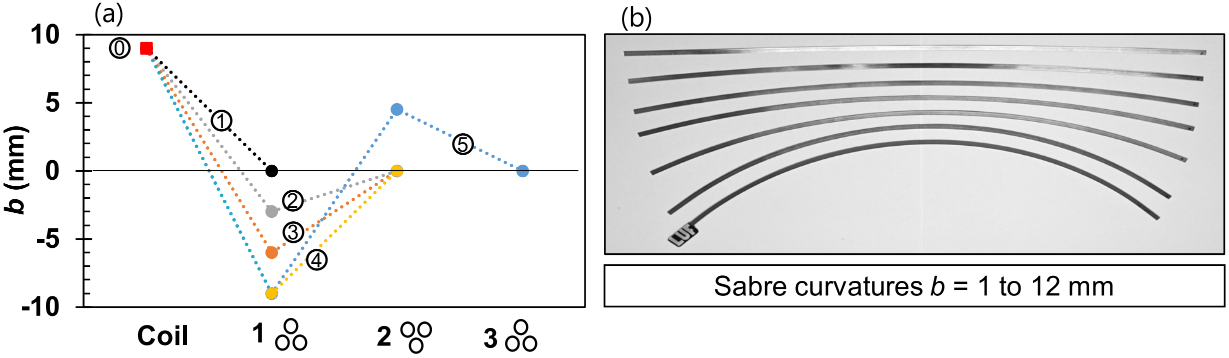


Fig. 3 (a) Potential straightening strategies to be assessed. (b) Examples of sabre curvatures.

The above-described guideline for the calibration process makes it possible to follow the path of a defined straightening strategy. However, to decide which strategy is optimal, suitable indicators must be used. Therefore, Fig. 3 illustrates potential straightening strategies (*1-5*) to be assessed in the following. The initial curvature (*0*) of the wire (from the coil) is *b* = 9 mm on a 300 mm segment of a circle. Strategy *1* follows the idea of minimizing the forming operations, whereas strategy (*5*) features three forming operations. Strategies (*2-4*) are intermediate, with two forming operations and different target curvatures.

Materials and Methods

The tested material is an austenitic X10CrNi18-8 spring steel flat wire with a cross-section of 3.9 x 0.4 mm^2. Tensile testing is performed according to DIN EN ISO 6892-1 [8] with Zwick Z100 tensile testing machine. The criterion for evaluating the residual forming limit is defined as the integral of the tensile stress σ over the strain ε until fracture. Residual stress measurements were carried out according to DIN EN 15305:2009 [9] using X-ray diffractometer DR45 by Stresstech GmbH performing sin2ψ method in γ-Fe {311} lattice plane in the depth of approx. 6 µm. The stresses were measured in the centre on the outer and inner side (in relation to the coil winding) in the longitudinal direction of the 500 mm long wire segments.

Results

The first finding is that the above-described straightening process (using individual straightening modules) is a capable process, i.e. that the paths of the straightening strategy described in Fig. 3 (a) can be followed accurately. Especially, it is also possible to first straighten a wire and then form curvatures like a sabre with the modular 3D straightening-machine in a controlled manner (*cf.* Fig. 3, b). However, this freedom in the straightening process raises the question of which strategy should be chosen. Therefore, the evolution of the residual stresses and forming limits regarding the different straightening strategies have been investigated. These two aspects are considered to be antagonistic constraints when optimising straightening strategies.

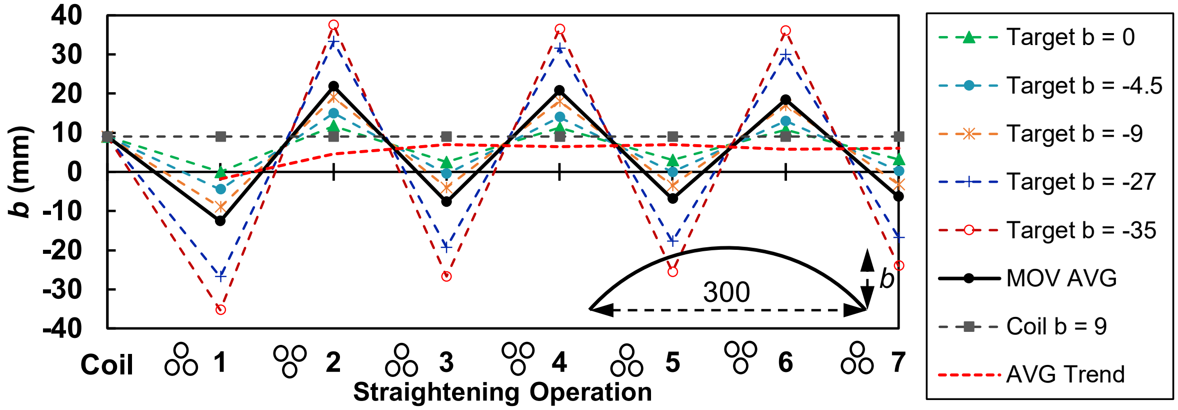


Fig. 4 Evolution of the curvature b in the reverse straightening experiment for the target values b = 4.5, 0, -4.5, -9, -27, -35 mm and an initial curvature of b = 9 mm on a 300 mm segment of a circle.

First, the influence of the inhomogeneous properties of the wire are illustrated using a straightforward experiment. The reverse straightening experiment follows the hypothesis that a homogeneous wire regains approximately its initial curvature when it is passed through the straightening machine again with the same straightening parameters but upside down. This should apply in particular if the aim is to mirror the initial curvature (9/-9/9/...). The six target curvature values *b* = 4.5, 0, -4.5, -9, -27, -35 mm are reached accurately with the first forming operation. Then, six alternating forming operations are performed and evaluated. Fig. 4 shows that the resulting curvatures of the second and third straightening operations do not fulfil the hypothesis. This is attributed to the initial inhomogeneity and residual stresses distribution of the wire. The deformation releases the inhomogeneity, which manifests as springback, especially after the first straightening process. This is likely to be caused by the misfit of the residual and load stresses. Then, after the third straightening operation, an almost stationary and alternating path results, which indicates homogeneity (indicated by the average trendline) and thus fulfils the initial hypothesis.

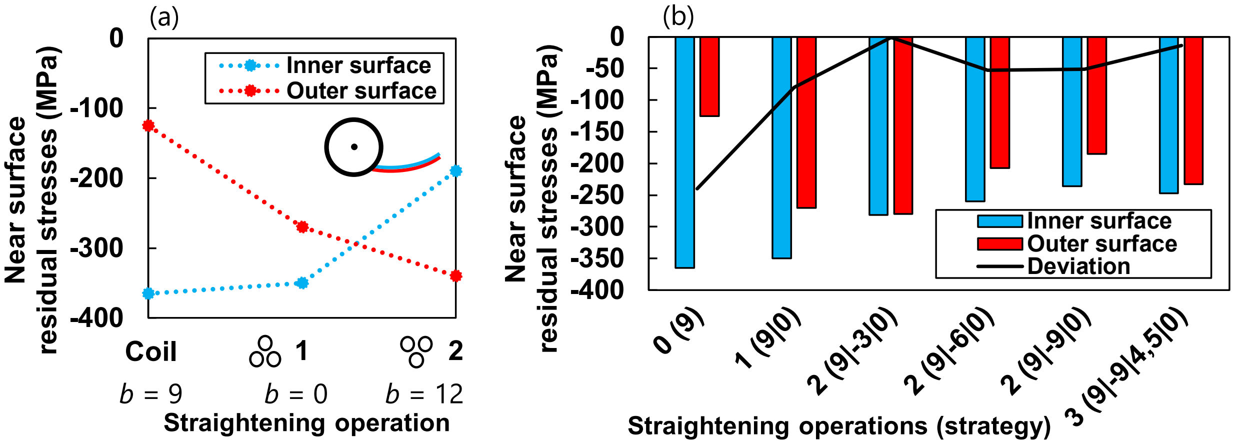


Fig. 5 (a) Near surface residual stress measurements depending on the number of straightening operations with the same position of the roller z (reverse straightening experiment: target b = 0). (b) Near surface residual stress measurements in dependence of the number of straightening operations and the strategy.

Near-surface residual stress measurements were performed to confirm the observation of the preceding reverse straightening experiment and to establish the basis for the optimization process of straightening strategies. At first Fig. 5 illustrates the initial inhomogeneous residual stress distribution of the wire taken form the coil (straightening operation/strategy 0), stated by a deviation from the inner to the outer surface of approx. 240 MPa. This stress distribution counters a homogeneous forming behaviour, as the major deformation in the straightening process takes place in the surface layer. Fig. 5 (a) shows the corresponding residual stress evolution in the reverse straightening experiment for target value *b* = 0 for the first two straightening operations. The inhomogeneity is reduced but not eliminated. This measurement proves the superposition of an inhomogeneous residual stress distribution with the load stresses, which was assumed in the evaluation of the reverse straightening experiment (cf. Fig. 4). Due to the residual stress distribution, the tensile load on the inner surface layer is reduced, and the compressive load on the outer surface layer is increased in the first forming process. Since a smaller curvature occurs after the first straightening operation than in subsequent straightening operations, it is considered that the decrease in tensile load on the inner surface layer is dominant, although a definite assessment is not possible for the time being without a complete residual stress depth evaluation. Vice versa, this leads to the conclusion that the reverse straightening experiment is a useful method to determine the effect of the residual stresses, which in the case of straightening is considered more relevant than determining the residual stresses per se.

Fig. 5 (b) shows the residual stress distributions and deviations between the inner and outer surface in dependance of the number of straightening operations and straightening strategy. It can be seen that the level of residual stresses is not significantly reduced by straightening. However, the deviation of the residual stress distribution is significantly reduced, and thus homogeneity is achieved. In particular, a higher number of straightening operations (>1) tends to lead to a greater reduction in the deviation of the near-surface residual stresses. But, with a measurement uncertainty of 60 MPa in the confidence interval of 95 %, this tendency is considered less significant regarding the selection of the straightening strategy.

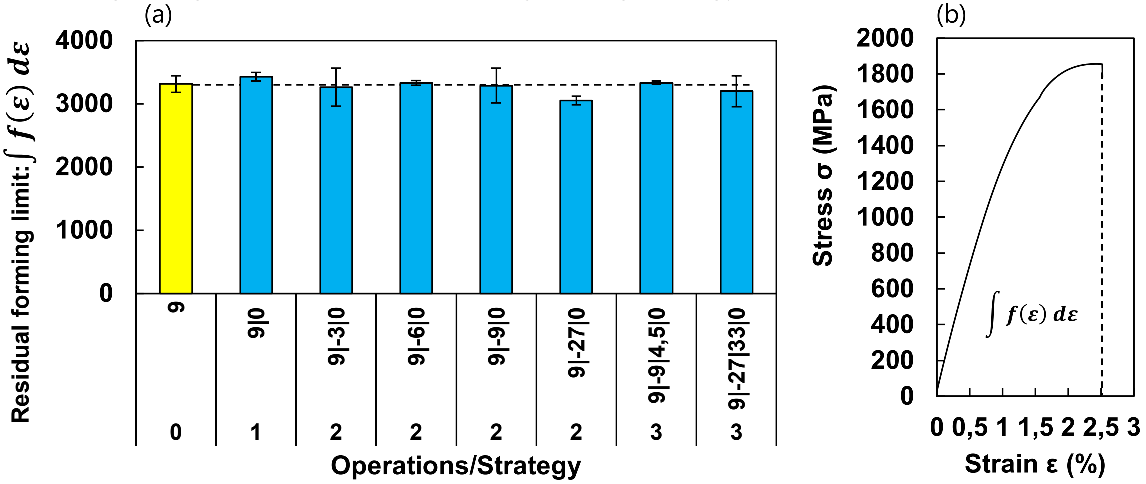


Fig. 6 (a) Residual forming limit in dependence of the number of straightening operations and the strategy. (b) Stress-strain-curve of the flat wire with initial curvature of b = 9 mm (from coil).

Another key indicator for defining a straightening strategy is the residual forming limit. Therefore, the influence of different straightening strategies on the residual forming limit was investigated. Fig. 6 (a) shows a trend towards a slight reduction in residual forming limit, but with the standard deviation of the test points being greater than the observed effect. In this context, it has to be considered that with a high-strength spring wire, a significant change in the residual forming limit is not to be expected because it has a long history of forming operations and thus has been strongly affected by work hardening. We therefore conclude that within the limits of the investigated straightening strategies there is no influence on the residual forming limit.

Conclusion and Outlook

In conclusion, the modular design is an advance in straightening technology, enabling low set-up times without extensive material testing. The operator does not need to have a detailed knowledge of materials science and testing. Furthermore, the modular design is the key to optimising the straightening strategy. By isolating the levelling processes and thus eliminating the interactions between the straightening operations, the process becomes controllable. The mere fact that a defined strategy can be easily followed ensures that more residual forming limit will be retained than in conventional straightening processes.

The residual stress analyses show that significant homogenisation is already achieved with a single straightening operation. However, the residual stresses are not significantly reduced, which is usually not necessary with the present compressive residual stresses. But, as these measurements have near-surface and microscopically resolution, further investigations with in-depth and macroscopic resolution are required. An (optical) hole-drilling-method [10] is therefore being adapted in parallel to this work with regard to the wire-specific challenges. However, even without this knowledge, the actual material behaviour, i.e. the sum of the actual material properties of the wire, including residual stresses, is determined by the calibration process of the modular straightening machine. In this context the developed reverse straightening experiment is a useful method to determine the effect of the residual stresses, especially their inhomogeneity, which in the case of straightening is considered more relevant than determining the residual stresses profiles per se.

Regarding the variations in wire properties that occur during the continuous straightening process, an online-control design and a corresponding compensation strategy are required. Here, it appears to be most sensible to pursue the objective of controlling the straightness at the last straightening module of each type because this does not cause any interactions with preceding straightening operations. This possibility is a key benefit of the modular design compared to the conventional straighteners. However, it is necessary to find measurable process quantities that enable a closed-loop control. These may include force, eddy current or tactile and optical curvature measurements of the straightening process or the subsequent processes.

Acknowledgement

The authors would like to thank the German Federal Ministry of Economics and Climate Protection for funding this research project: "Development of an innovative straightening machine for three-dimensional straightening and forming", (AiF Research Association: FOSTA-No. 1565, IGF-No. 22114 N / 1).

References

[1] P. Enghag, Steel wire technology, Materialteknik HB, Orebro, Swedan, 2004.

[2] E. Doege, R. Menz, S. Huinink, Analysis of the levelling process based upon an analytic forming model, CIRP Annals - Manufacturing Technology 51 (2002) 191–194. https://doi.org/10.1016/S0007-8506(07)61497-8

[3] P.J. Withers, Residual stress and its role in failure, Rep. Prog. Phys. 70 (2007) 2211–2264. https://doi.org/10.1088/0034-4885/70/12/R04

[4] W. Guericke, M. Paech, E. Albert, Simulating the wire straightening process, Wire Technology International 8 (1996).

[5] I. Khromov, R. Kawalla, Simulation of a steel wire straightening taking into account nonlinear hardening of material, Eng. Technol. Appl. Sci. Res. 2 (2012) 320–324. https://doi.org/10.48084/etasr.275

[6] W. Guericke, Material model describing cyclic elastic-plastic deformation of roller levelling and straightening processes, steel research international (2009).

[7] M. Grüber, L. Kümmel, G. Hirt, Control of residual stresses by roller leveling with regard to process stability and one-sided surface removal, Journal of Materials Processing Technology 280 (2020) 116600. https://doi.org/10.1016/j.jmatprotec.2020.116600

[8] DIN EN ISO 6892-1:2020-06, Metallic materials - Tensile testing - Part 1: Method of test at room temperature (ISO 6892-1:2019); German version EN ISO 6892-1:2019, Beuth Verlag GmbH, Berlin.

[9] DIN EN 15305:2009-01, Non-destructive testing - Test method for residual stress analysis by X-ray diffraction; German version EN 15305:2008, Beuth Verlag GmbH, Berlin.

[10] F. Dahms, W. Homberg, Investigations and improvements in 3D-DIC pptical residual stress analysis—A new temperature compensation method, in: G. Daehn, J. Cao, B. Kinsey, E. Tekkaya, A. Vivek, Y. Yoshida (Eds.), FORMING THE FUTURE: Proceedings of the 13th international conference on the Technology of Plasticity, Springer Cham., 2021, pp. 2249–2259. https://doi.org/10.1007/978-3-030-75381-8_189