Roller straightening process and peripherals

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The manufacturing of high quality wire products needs defined properties of the wire which can be received by wire straigthening. To optimize the straightening process it is necessary to identify the straightened material and its production history before. This article describes identification methods and procedures for applying the straightening process to receive a specified wire quality.

In a technological line for the production or processing of single or multiple wire-like materials (fig. **1**), the roll-type straightening process is one element among many. Yet compared to the decoiling, guiding, conveying and processing elements of such a process chain, straightening is usually neglected. It is becoming increasingly clear, however, that the way in which the straightening process is designed and integrated is an important factor. The classical function of a straightening process is to create material which is straight or has a defined curvature, but today straightening is also expected to perform a number of other jobs as well, such as identifying the material's characteristics and changing them in a predefined manner. With the identified or specially adapted characteristics it is then possible to optimize the material's processing on follow-up machines.

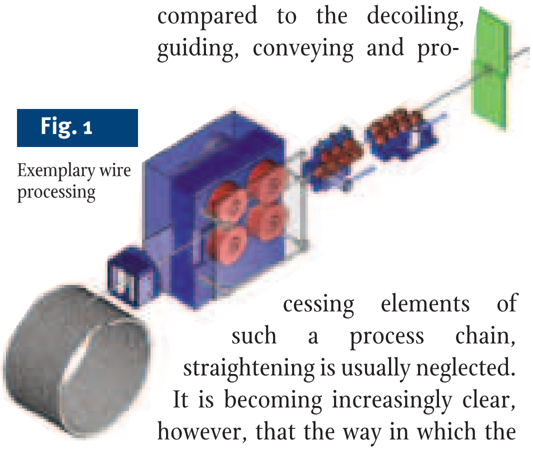


Fig. 1

Exemplary wire processing

While the actual design of a straightening process depends above all on a wire's characteristics such as its cross-sectional geometry, yield point, modulus of elasticity, initial curvature and helix [1, 2], its integration in a production line must take place with due consideration to both the upstream and downstream processes, machinery and equipment. Strategies and proposals for integrating the straightening process are presented in [3] and, suitably optimized, can serve as a basis for achieving high-quality final products at the end of a technological line. A holistic approach – extending also to identification – receives special attention in this connection.

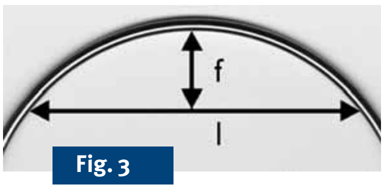


Fig. 3

Identification of the deflection f over the length l

Identification of the straightened material production

When planning the production of straightened material it is first necessary to establish and identify the processes involved. It makes sense to concentrate on the essentials, meaning in particular those forming processes which immediately precede the straightening process. These

Fig. 2

Idealized distribution of strain and stress during the bending of a process material

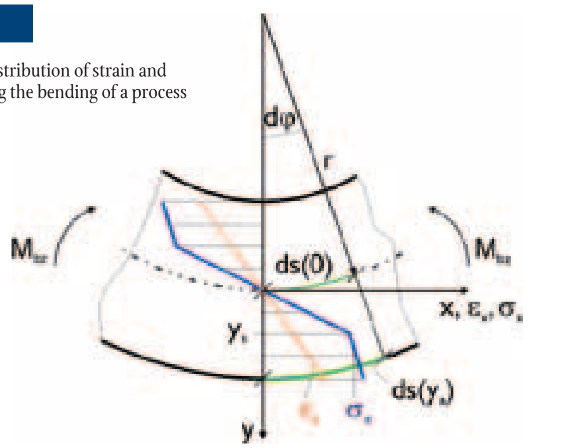


Fig. 4

The measured form curve y(x) and resulting curvature characteristic κ(x) of a wire section

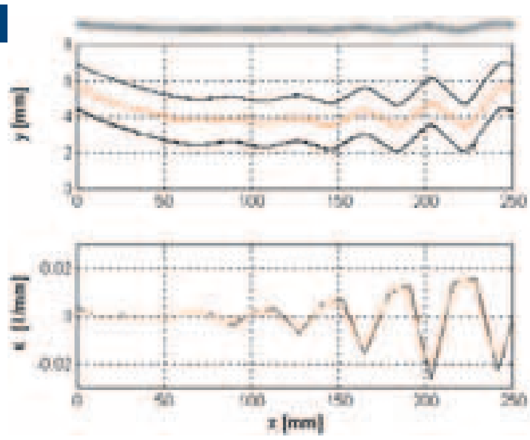
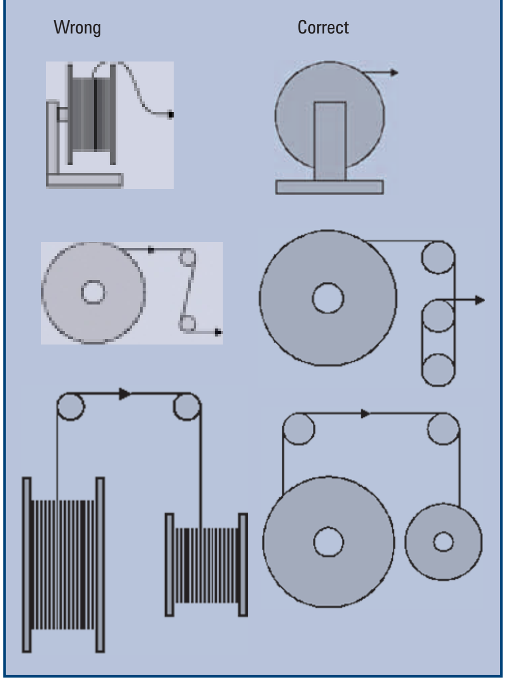


Table 1: Examples of how to prevent mistakes during the unwinding of material



include, for example, rolling, drawing, winding, unwinding and deflecting. Each single process affects the material in a unique and special way, a fact which ultimately finds expression in the stresses which arise and/or remain within the straightened material. The type of stress created under load is characterized by the type of load. For example, tensile forces (from drawing, winding, unwinding) result in tensile stresses, bending forces (from deflecting) result in bending stresses. Fig. **2** shows, by way of example, the idealized distribution of strain and stress during the bending of a process material.

In the course of planning the production of straightened material it is important to subject each of the processes involved to critical review. Assuming that all the processes are suitable it is then necessary to consider aspects such as the degree of forming, deformations, die geometry and material grade, and to make modifications as required. It is nearly always cheaper to examine the start-up conditions and implement the findings than it is to tackle unwelcome results further down the line.

Often it suffices to consider the deformations which occur when a material is unwound or decoiled. A material which is subjected to non-uniform changes of direction, particularly using undersized guide rollers, will be left with internal stresses that are non-constant and disadvantageous for all follow-up processes.

Table **1** shows the kind of mistakes which can occur during unwinding and what can be done to help obtain final products of constant and high quality. First one should ensure that the direction of guidance complies with the material's primary curvature on the reel. Second it is important to check that the diameter of the guide rollers will ensure elastic deflection. This depends on the radius of curvature r, the cross-sectional height of the material (for round wires the wire diameter d), the yield point R_p and the modulus of elasticity E. Equations 1 and 2 can be used to calculate the minimal guide roller diameter D_{min} and the maximal D_{max}.

$$D_{\min} = 2 \cdot \left[\frac{d \cdot E \cdot r}{d \cdot E + 2 \cdot R_p \cdot r} \right] \quad \text{Eq.1}$$

$$D_{\max} = 2 \cdot \left[\frac{d \cdot E \cdot r}{d \cdot E - 2 \cdot R_p \cdot r} \right] \quad \text{Eq. 2}$$

Analysis of the straightened material and requirements at the final product

Analyzing the straightened material and defining the requirements imposed on the final product are tantamount to identifying and specifying the material's characteristics before and after the straightening process. Characterization has to be based on the relevant geometrical parameters and material data. The geometrical parameters boil down to:

– cross-sectional geometry
– curvature or radius of curvature
– range of curvature
– helix

It is usually an easy matter to determine the cross-sectional geometry, e.g. of the wire diameter. Conclusions about the other geometrical parameters are often impossible, however. The minimal requirement for designing and integrating a straightening process is to determine the curvature or radius of curvature in relation to one dimension. Given the material's deflection f over the length l as shown in fig. **3**, equation 3 can be used to calculate the radius of curvature r. Equation 3 also shows that the curvature κ is the reciprocal value of the radius of curvature r.

Fig. 5

Fuzzy system for calculating the necessary number of straightening rolls n

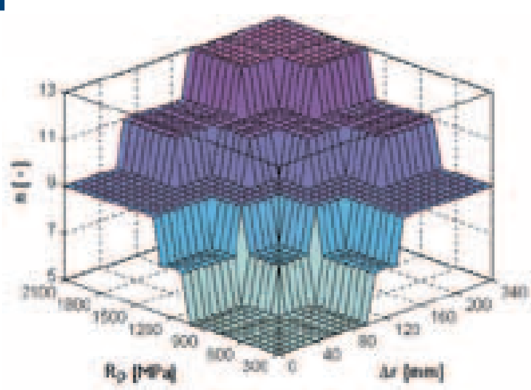
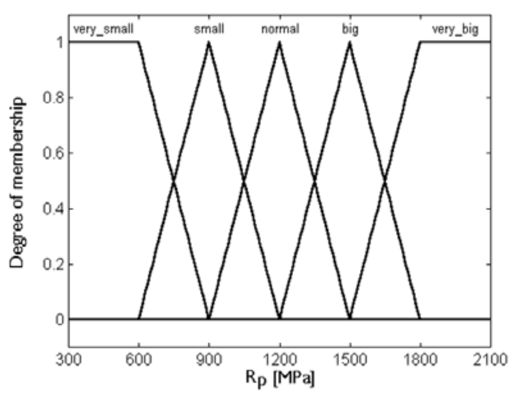


Fig. 6

Membership functions of the input variable R_p (yield point)



$$r = \frac{1}{\kappa} = \frac{f^2 + \left(\frac{l^2}{4}\right)}{2 \cdot f} \qquad \text{Eq. 3}$$

A secondary curvature of smaller radius is often superimposed on a primary curvature with radius r. Alternating curvatures exist therefore along the length of the material and can only be determined through exact plotting of the material's form curve and use of equation 4. The characteristic of curvature κ as a function of length x results when incorporating the 1st and 2nd derivative of the form curve y(x).

$$\kappa(x) = \frac{y''(x)}{\sqrt{\left(1 + y'(x)^2\right)^3}} \qquad \text{Eq. 4}$$

Witels-Albert has measuring stations which enable the automatic measurement of form curves y(x). Image processing is used, for example, for round wires of up to 3.0mm in diameter. Fig. **4** shows the form curve and the curvature characteristic $\kappa(x)$ for a section of wire. The difference between the maximal curvature κ_{max} and the minimal curvature κ_{min} results in the curvature range $\Delta\kappa$ (Equation 5).

$$\Delta\kappa = \left|\kappa_{max} - \kappa_{min}\right| = \left|\frac{1}{r_{min}} - \frac{1}{r_{max}}\right| \qquad \text{Eq. 5}$$

A curvature in the second dimension results in a material with a helix, which is characterized by a radius r and a pitch P.

For the material straightening process – and for the processes which follow it – nothing is more interesting than the material data

– modulus of elasticity,
– yield point,
– tensile strength,
– modulus of hardening and
– residual stress potential.

All these data – apart from residual stress potential – can be determined with sufficient accuracy using, for example, the tensile test compliant with DIN EN 10002. It should be noted that it is only marginally important to know the tensile strength when designing a straightening process. Fact is, to achieve a permanent change of form by straightening it is necessary for the material to undergo an elastic-plastic deformation while retaining its cross-sectional area. The critical parameter in such an elastic-plastic deformation is the material's yield point and not its tensile strength; deformation at or above the material's tensile strength is normally accompanied by a change of cross-sectional area, leading to failure by breakage.

There is a relationship between a process material's residual stress potential and its outer form. If no external forces and moments act on the material, its form curve does not change because the sum of its own forces and moments is in equilibrium. If parameters such as curvature or helix change over the length of the material, so do the residual stresses. Straightening changes the residual stresses so that the state of residual stress existing in the non-straightened material is erased after just a few elastic-plastic deformations [4]. When it comes to identifying residual stresses, there are several rival principles to choose from. Unfortunately, a comparison of mechanical, X-ray, magnetic, neutron beam and ultrasound methods shows that they often deliver quantitatively differentiated results; a single option should be used, therefore, to derive qualitative conclusions.

Designing the straightening process

The way the straightening process is designed will be reflected in a straightening system defined by a combination of a straightening units designed to create constant material characteristics through adaptation to the changing characteristics of the feed material. Every straightening unit and every straightening system has a specific straightening range which is fixed by the spacing and the diameter of the straightening rollers. The straightening range Δ thus has limits for the minimal and maximal cross-sectional dimensions of material to be straightened. For round wires, for example, the relevant parameters are the minimal wire diameter d_{min} and the maximal wire diameter d_{max} (Equation 6).

$$d_{\min} \le \Delta \le d_{\max} \qquad \text{Eq. 6}$$

Once the straightening range is fixed with due consideration to the material's cross-sectional dimensions, the next step is to decide on the number of straightening rolls. In [2] an attempt was made to recommend a method of calculating the number of rolls for a straightening unit on the basis of a material's curvature range $\Delta\kappa$ and yield point range ΔR_p. The limited validity of the specification published in [2] for calculating the number of rolls prompted new investigations which have shown, for example, that the absolute value of the yield point R_p should be taken into account rather than the yield point range ΔR_p. In the new approach, fuzzy logic is used instead of a rigid calculation specification.

Table 2: Values for the number of straightening rolls n calculated with fuzzy logic

Range of initial curvature radius Δr [mm]	Yield point R_p [MPa]	Number of straightening rolls n [-]
0	1000	5
60	1000	7
100	1000	9
100	2000	11
160	2000	13

Given the difficulties of establishing the number of rolls by mathematical means, use is made instead of a knowledge base consisting of the linguistic terms (membership functions) of the input and output variables, a rule base and the inference and de-fuzzifying mechanisms. The knowledge which is channeled into the fuzzy system (fig. **5**) is the result of empirically established and verbally formulated rules and is based in addition on the results of putting the virtual simulation of the straightening process to actual use [5].

Via the rule base, consisting of 25 rules, the input variables Δr and R_p are linked to the output variable n (representing the number of straightening rolls). A sharply defined value for the input variable "radius of curvature range Δr" can be calculated with equation 7. The variables r_{max} and r_{min} are the maximal and minimal radii of curvature determined with equation 3.

$$\Delta r = \left| r_{\max} - r_{\min} \right| \qquad \text{Eq. 7}$$

The membership functions of the input variable yield point R_p are laid down in fig. **6**. The fuzziness is particularly evident in the overlapping of the variable sets. For example, an elongation limit R_p = 800 MPa at 33 % (degree of membership μ = 0.33) is assigned to the set *very_small* and at 67 % (degree of membership μ = 0.67) to the set *small*.

Use of a suitable inference mechanism and a specific de-fuzzifying method results finally in a specific conversion characteristic as shown in fig. **7**, which can be used at any time to generate a sharply defined output variable for a set of sharply defined input variables. Table **2** presents derived values of n (the number of straightening rolls) for a number of discrete values of the input variables R_p (yield point) and Δr (radius of curvature range).

A further factor – in addition to the straightening range and number of straightening rollers with a major impact on the straightening process – is the way in which the straightening rolls are positioned; after all, it is the positions of the straightening rolls which influence the bending operations and hence the residual curvature. Witels-Albert has developed various levels of technology which differ in their degree of automation. In conventional straightening systems, simple tools are used to position the rolls. Another possibility are adjusting elements equipped with a position gauge or vernier scale. Advanced straightening technology featuring a high degree of automation, e.g. semi-automatic straightening units and systems [6] or automatic roll actuators [7] can position the straightening rolls with reproducible high precision within a very short time. Software is a key component of the overall system at each of these two levels of technology. Whatever the degree of automation, Witels-

Fig. 7

Correlation between the input variables and the number of straightening rolls n

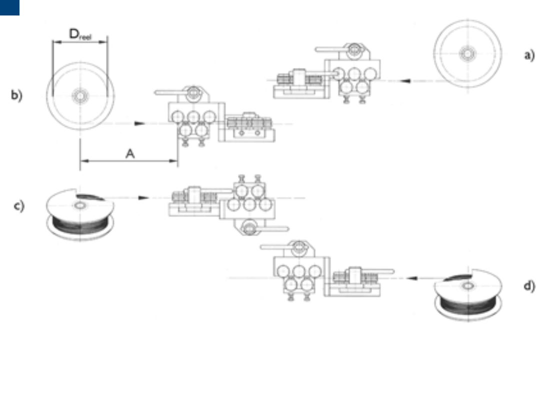
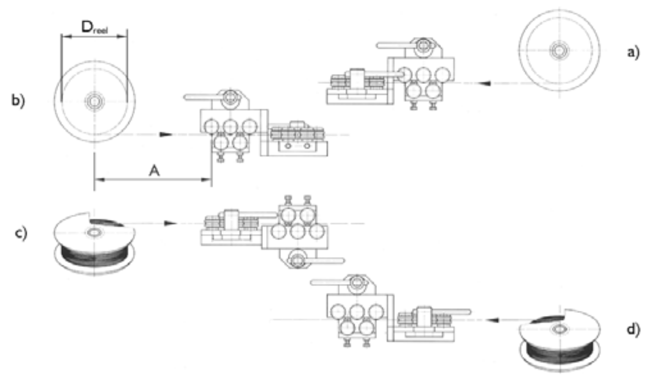


Fig. 8 Various ways of arranging a straightening unit or system



Albert uses a simulation program [5] to determine the roll adjustment values.

Integration of the straightening process

In spite of the great diversity of processes which can take place upstream or downstream from the straightening process, it is possible nevertheless to draw up a number general rules of integration for all cases.

First is to ensure the zero line as presented, for example, in fig. **8a**. This means that the tools involved in the processes along a processing line are positioned relative to defined geometrical boundary conditions so that they only touch a material of specific size, i.e. no deformations occur within the zones of impact of the tools. Exceptions are inevitable interruptions to the zero line, e.g. in the form of material deflections. Positioning of the tools – including those of a straightening unit or system – must always be defined in relation to the zero line so that random tool positions can be reproduced at any time.

Even when the zero line is assured there is, theoretically, still an infinite number of ways to adjust a straightening unit or system; rotation around the zero line, rotation around the normal vector to the zero line and displacement in the direction of the material are all conceivable.

The reciprocal arrangement of a straightening unit's rolls in one plane and the objective of performing (n-2) effective bending operations with n straightening rolls give rise to a first compulsory condition which restricts the above mentioned rotations to one angle in each case. Applying this compulsory condition results in a total of eight different ways of arranging a straightening unit or system, four of which are illustrated in fig. **8**. One application must be such that the axis of the first straightening roll in the transport direction of the material is parallel to the axis of the upstream reel or guide roller and that both axes are on the same side relative to the zero line. An adequately bent material can take the place of the upstream reel or guide roller.

The exact arrangement of the straightening process in the transport direction of the material is derived from a second compulsory condition which defines the distance A (equation 8) to a process upstream from the straightening process.

$$A \leq \pi \cdot D_{reel} \qquad \text{Eq. 8}$$

Maintaining the distance A marked in fig. **8b** ensures a constant quality of straightening. If the distance A – calculated with allowance for the reel diameter D_{reel} – is not respected, the still curved material will be able to twist before it reaches the straightening unit or system and also while it is inside the unit or system. The moment vectors of the bending operations are stochastic in their alignment and lead to negative deformations and a variable, poor quality of straightening.

Conclusions

The optimal design and integration of a straightening process requires in advance identification of the straightened material and its production. Similarly, the requirements to be met by the final product need to be defined and taken into account. Objective and established possibilities of identification are available and should therefore be used as standard practice in the wire industry. Clear-cut guidelines, based in part on the use of state-of-the-art methods and procedures, exist for the design and integration of straightening processes. Guidelines for the identification of a straightening process are structured on the basis of an interdisciplinary approach covering those processes which take place both upstream and downstream from the straightening process.

To promote the use of an interdisciplinary approach Witels-Albert has published a book [8] and created a questionnaire [9] to provide support with the identification, design and integration of straightening processes. At the same time the company also supplies products that link the straightening process to upstream and downstream processes with optimum effect and which represent integration options embodying the state of the art.

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