Tensile force requirement for the straightening of wire with roller straightening units

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Calculation specifications recommended for determining the tensile force requirement for straightening with roller-type straightening systems supply only rough approximations. A new model for calculating the tensile force requirement was developed selectively on the basis of a requirements profile. It takes account for the first time of the straightening unit's geometrical boundary conditions as well as the properties of the process material. Calculations carried out for an exemplary selection of wires using the new model display a very good correlation with the measured values.

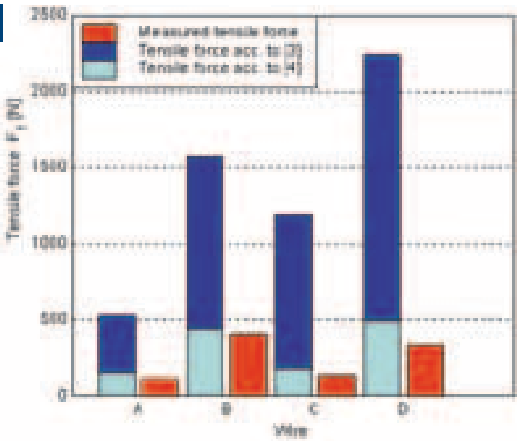
Conventional and innovative technology [1, 2] for the straightening of wire has a very large field of application, ranging from wire rolling mills and wire drawing plants to the manufacturers of finished and semi-finished wire products. Accordingly the possibilities of working wire are numerous. Straightening units are employed not only as autonomous tools in higher-level processes but also as elements in machines for a variety of purposes. Apart from producing straight wire they are frequently used to create a defined residual bend.

Whatever the details of the specific cases of application may be, they all have one thing in common: the need to transport the process material relative to the straightening unit. Process design and the selective planning and construction of machinery are impossible without an exact knowledge of the tensile forces needed to transport the process material. Fact is, these tensile forces have a dominant influence on potential process speeds and on essential power ratings. And knowing them can also have a positive effect when they are used to optimize the consumption of energy per unit as laid down in the standards concerning environmental management systems, e.g. ISO 14000 ff.

Analysis

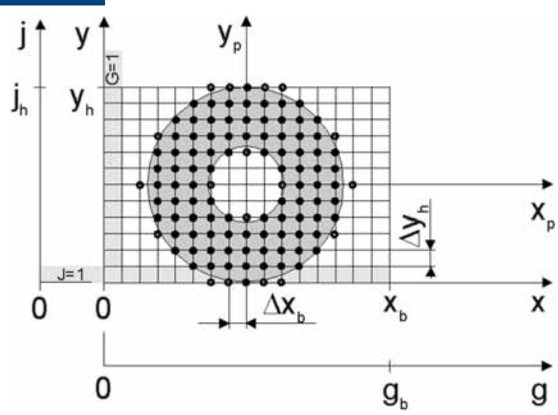
In spite of this need for knowledge of the tensile forces, today's state of the art for their determination is limited to a few specific and expensive straightening tests and measurements or to calculations able to provide only rough tensile force approximations. In [3], for example, there is an explanation of how to calculate the greatest force for drawing a wire through a roller straightening unit with n rollers. Initial and residual bends of magnitudes corresponding to the reciprocal value of the roller radius are presumed for all the (n-1) bending operations performed. The solution applies for round wires with an ideal elastic-plastic material characteristic, a condition that is hardly relevant for the wires used in practice. The contents of [3] are supplemented in [4] where an approxima-

Fig. 1



Comparison of the tensile force requirement according to [3] and [4] with measured values

Fig. 2 Division of the cross section in elements



tion in the form of an arc is introduced for the bend of the process material in the area of influence of an active-bending roller. Account is taken for the first time ever of both the pitch, i.e. the distance from one straightening roller to another, and the roller adjustments, albeit for the sole case of parallel adjustment in which all the rollers have identical adjustment values in relation to the wire-specific zero line.

Fig. **1** compares the results of tensile force calculations according to [3] and [4] with the measured results for the straightening of selected wires on a roller-type straightening unit. Table **1** and **2** lists the parameters of the unit used and the properties of the wire. Increasing the bend radius in the areas of influence of the active-bending rollers in accordance with [4] leads to a considerable reduction in the results of the calculated tensile force compared to the results according to [3]. Table **2** shows the relative error ε_r of all the calculated results in relation to the measured results. The tensile forces are always overestimated, also when proceeding in accordance with [4], with excessively large deviations occuring in particular for the wires A, D and E. Determining the tensile force requirement in accordance with [3] is not recommended under any circumstances.

Table 1: Parameters of the straightening system

Straightening unit	RB 11-3 CS
Number of rollers n	11
Outer ∅ of straightening roller D_A [mm]	31
Roller profile groove width B [mm]	3.2
Roller profile groove angle α [°]	90
Roller pitch T [mm]	19

Table 2: Parameters of selected wires and relative error in forecasts of tensile forces

Wire		A	B	C	D
Wire ∅ d	[mm]	1.55	2.00	1.5	1.9
Yield limit R_p	[MPa]	725	1000	2110	1800
Modulus of elasticity E	[MPa]	190190	181380	199880	188720
Initial bend κ^*_a	[–]	-0.7	-0.6	-0.26	-0.33
Relative error ε_r for tensile force according to [3]	[%]	366	293	755	559
Relative error ε_r for tensile force according to [4]	[%]	33	9	33	44

Requirements

From this short analysis of the known options available for calculating the tensile force it is possible to derive a clear picture of what is needed. Apart from being innovative and quicker than taking measurements, the solution should have the following features:

– It must be possible to calculate the tensile force for any straightening unit, with due account taken of its geometrical boundary conditions such as number of rollers, roller diameter, roller profile, pitch and adjustments.
– Regardless of the method of adjustment it must be possible to achieve calculated results with a relative error in the range of $-10\% \leq \varepsilon_r \leq 10\%$ in relation to the corresponding measured values.
– The initial bend range or initial bend and the required residual bend have to be included in the problem-solving procedure.
– Each bending operation is decisively affected by the deformation characteristic of the specific material, hence it is necessary to integrate a capable material model.
– Exact determination of the process material's bending line in correlation with the bend characteristic is an important condition for calculating the tensile force; otherwise it is impossible to identify the exact moments at the active-bending rollers.
– Considering the large assortment of material cross sections, it has to be possible to calculate the tensile force not only for round wire but for any cross sections.

Model

Central element of the calculation model for tensile force from Witels-Albert is the analysis of a wire section on its way through the offset roller arrangement of a straightening unit in the light of the pre-given requirement profile. Under the influence of alternating bends, the bend of the wire section changes from roller to roller in the direction of the exit. A bending moment is assigned to each bend. The relationship between the bending moment and the bend is defined by the material and the cross sectional geometry of the process material and by the respective geometrical boundary condi-

Fig. 3

Approximation of material behaviour under alternating load deformation

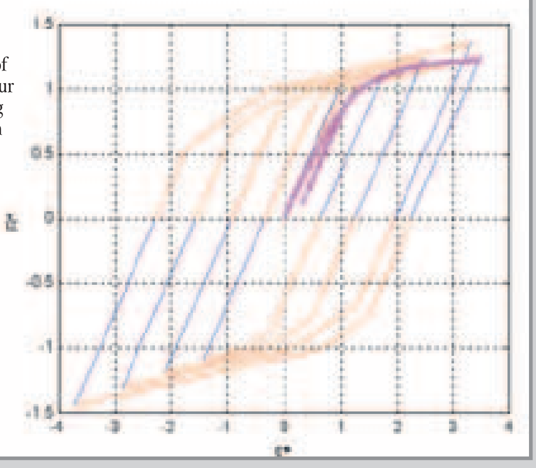
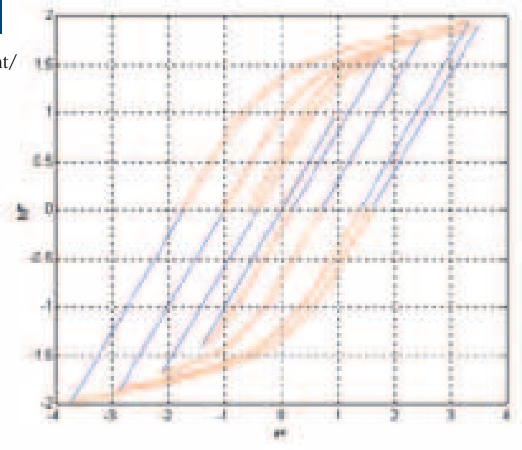


Fig. 4

Bending moment/ bend curves



tions. The work of deformation, which plays a dominant role in the tensile force needed to transport the process material, is derived from the relationship between bending moment and bend for each bending operation. Dynamic contents – caused by the forces and moments of mass inertia – and frictional contents are small and disregarded accordingly.

Bending moments and bends

A bending operation i in which the wire section is loaded and unloaded takes place in the area of influence of a straightening roller. The load can result in an elastic or an elastic-plastic deformation and is characterized by the initial state *[i0]* and the loading maximum *[iv]*. The loading is followed – starting from the loading maximum *[iv]* – by unloading to the final state *[(i+1)0]*, which at the same time represents the initial state of the next bending operation. The characteristic variables of the wire section such as strain, stress, bend and bending moment change from the start of the loading to the end of the unloading. A bending moment/bend curve for a bending operation i is a determinate representation of the bend κ_i at the bending moment M_i (Equation 1).

$$M_i = f(\kappa_i) \qquad \text{Eq. 1}$$

For the numerical generation of bending moment/bend curves for all bend operations i it is necessary to know the corresponding bend of the loading maximum. [5] reports on an algorithm for calculating the bending line of the process material between the individual straightening rollers, which at the same time also supplies the reference adjustment-related bends κ^*_{iv} for the loading maximums, provided the reference initial bend $\kappa^*_a = \kappa^*_{10}$ of the process material is given.

The advantage of using reference variables, which are always marked with an asterisk, is that it simplifies the modeling. Equation 2 states, for example, that the reference bend κ^*_{iv} of the reference strain of the outer fibers of the process material equals ε^*_{iav}. From the reference bend or strain it is possible – with the strain limit R_p and the modulus of elasticity E – to calculate the strain of the outer fiber ε_{iav} in the non-referenced representation. With the cross section height H it is possible at any time to derive the bend radius r_{iv} correlating with the strain ε^*_{iv} .

$$\kappa^*_{iv} = \varepsilon^*_{iv} = \varepsilon^*_{iav} = \frac{E \cdot \varepsilon_{iav}}{R_p} = \frac{E \cdot H}{2 \cdot R_p \cdot r_{iv}} \qquad \text{Eq. 2}$$

Calculating a bending moment/bend curve requires the discretization of the reference bend κ^*_i for the loading and unloading of a bending operation i. A discrete value for the bending moment M^*_{id} has to be calculated for each discrete bend κ^*_{id}. To make this possible for random cross sections the cross section of the particular wire section is divided into elements (fig. **2**). The grid extending over the cross section has j layer lines and g column lines. Each element produced by the grid is identified by the layer and the column and has a specific element area. Nodes arise when the points of intersection of the layer lines j and the column lines g lie in the cross section. Elements of the cross section are limited by at least three nodes, whereby a maximum n_j nodes exist for one layer line j and a maximum n_g nodes for one column line g. The number of nodes in j and g direction is determined by the particular cross section.

With the help of a material model the stress is determined for all the nodes, starting from the current value of the strain ε^*_{id} , which results from the discrete bend κ^*_{id}. The material model used to calculate the tensile force requirement makes allowance for the non-uniform expansion of the stress/strain characteristic given different directions of the main axes of stress (alternating deformation), also known as the *Bauschinger effect*.

Fig. **3** shows the modeling of the relationship between stress and strain for a layer of a wire section (outer fiber). Crosses mark the measured reference values of an exemplary initial loading of the wire B (Table **2**), which were determined by means of a tensile test in accordance with DIN EN 10002.

Having determined the node stresses using the described material model, the stresses of the nodes of two neighboring layer lines are averaged to obtain the relative layer stress $R^*_{id}(J)$. Multiplying with the layer area $A^*(J)$, obtained from the

Table 3: Calculation of total tensile force requirement F_{ZR}

Calculated tensile force F_{iZR} [N]	A			B			C			D		
Bending operation i	κ^*_{iv} [-]	a_i [mm]	F_{iZR} [N]	κ^*_{iv} [-]	a_i [mm]	F_{iZR} [N]	κ^*_{iv} [-]	a_i [mm]	F_{iZR} [N]	κ^*_{iv} [-]	a_i [mm]	F_{iZR} [N]
1	3.91	1.785	6.04	3.99	2.117	19.53	1.56	1.632	4.31	1.93	1.581	10.89
2	-4.23	0.000	9.99	-4.26	0.000	31.86	-1.79	0.000	4.76	-2.21	0.000	14.57
3	3.86	1.005	9.77	3.79	1.226	28.91	1.87	1.483	7.98	2.19	1.262	18.11
4	-3.36	0.000	7.89	-3.29	0.000	22.25	-1.85	0.000	7.55	-2.07	0.000	15.20
5	2.88	0.654	5.83	2.83	0.828	16.16	1.81	1.400	7.09	1.94	1.094	12.00
6	-2.41	0.000	3.92	-2.41	0.000	10.94	-1.77	0.000	6.32	-1.82	0.000	9.14
7	1.94	0.443	2.10	2.01	0.589	6.43	1.72	1.343	5.47	1.71	0.982	6.76
8	-1.48	0.000	0.64	-1.63	0.000	2.72	-1.64	0.000	4.47	-1.56	0.000	4.28
9	0.91	0.298	0.00	1.06	0.426	0.10	1.29	1.299	1.35	1.18	0.900	0.62
F_{ZR} [N]	46.2			138.9			49.3			91.6		

Table 4: Measurement of total tensile force requirement

Measured tensile force F_{ZMv} [N] Experiment v	A	B	C	D
1	45	131	50	91
2	43	132	50	91
3	44	133	51	92
4	45	133	50	90
5	45	134	51	93
$\overline{F}_{ZM} \pm S_{\overline{F}}$ [N]	44.4 ±0.4	132.6 ±0.6	50.4 ±0.3	91.4 ±0.6

sum of the individual element fill factors produces the force of one layer $F^*_{id}(J)$ (Equation 3).

$$F^*_{id}(J) = A^*(J) \cdot R^*_{id}(J) \qquad \text{Eq. 3}$$

Multiplying the layer force $F^*_{id}(J)$ by the distance to the uncut fiber of the cross section results in the layer moment $M^*_{id}(J)$ (Equation 4).

$$M^*_{id}(J) = F^*_{id}(J) \cdot y_I(J) \qquad \text{Eq. 4}$$

The total bending moment for the discrete bend κ^*_{id} results from the sum of the layer moments over the cross section (Equation 5).

$$M^*_{id} = \sum_{J=1}^{J=h} M^*_{id}(J) \qquad \text{Eq. 5}$$

The loading maximum with moment M^*_{iv} is reached when the discrete bend κ^*_{id} of the outer fiber equals the adjustment-related bend κ^*_{iv}, and the wire section enters the relief phase. It is assumed that all layers of the wire section return elastically to the load-free state, whereby the applied layer moment $M^*_{id}(J)$ is released in each case as the moment of elastic recovery. The correlating bend of the wire section at the end of a bending operation i is calculated with Equation 6.

$$\kappa^*_{[(i+1)0]} = \kappa^*_{iv} - M^*_{iv} \qquad \text{Eq. 6}$$

By way of example, fig. **4** presents the bending moment/bend curves for the bending operations performed on the wire B in a straightening unit in accordance with Table **1**. The reference initial bend κ^*_a is reduced to the residual bend $\kappa^*_r = 0$ by the deformations at the active-bending rollers.

Work of plastic deformation and the tensile force requirement

The work of deformation performed during a bending operation i on a wire section of length dx equals the impact of moment M_i over the angle of torsional bending $d\varphi_i$. Given

$$d\varphi_i = dx \cdot d\kappa_i \qquad \text{Eq. 7}$$

the work of deformation is

$$dW_i = W^*_i \cdot dW_p = = dx \cdot \int_{\kappa_i=\kappa_{i0}}^{\kappa_i=\kappa_{iv}} M_i(\kappa_i)\, d\kappa_i \qquad \text{Eq. 8}$$

If Equation 9 is used as reference value for the work of deformation dW_i on the wire section, then the reference work of deformation is calculated with Equation 10.

$$dW_p = M_p \cdot \kappa_p \cdot dx \qquad \text{Eq. 9}$$

$$W^*_i = \int_{\kappa^*_i=\kappa^*_{i0}}^{\kappa^*_i=\kappa^*_{iv}} M^*_i(\kappa^*_i)\, d\kappa^*_i \qquad \text{Eq. 10}$$

Like the bending operation, the work of deformation consists of an elastic and a plastic component. While the work of plastic deformation correlates with the tensile force requirement, the elastic component corresponds to a work or energy supply which flows back into the system. Hence the elastic component has to be subtracted from the work of deformation in order to obtain the plastic component (Equation 11).

$$W^*_{ipl} = W^*_i - W^*_{iel} = = W^*_i - \frac{M^{*\,2}_{iv}}{2} \qquad \text{Eq. 11}$$

From the energy balance according to Equation 12

$$F_{iZ} \cdot dx = dW_{ipl} = W^*_{ipl} \cdot dW_p = = \int_{\kappa^*_i=\kappa^*_{i0}}^{\kappa^*_i=\kappa^*_{iv}} M^*_i(\kappa^*_i)\, d\kappa^*_i - - \frac{M^{*\,2}_{iv}}{2} \cdot M_p \cdot \kappa_p \cdot dx \qquad \text{Eq. 12}$$

it is possible to derive the total tensile force requirement for straightening the wire section in a roller-type straightening unit with n rollers (Equation 13).

$$F_Z = M_p \cdot \kappa_p \cdot \sum_{i=1}^{n} \left[\int_{\kappa^*_i=\kappa^*_{i0}}^{\kappa^*_i=\kappa^*_{iv}} M^*_i(\kappa^*_i)\, d\kappa^*_i - \frac{M^{*\,2}_{iv}}{2} \right] \qquad \text{Eq. 13}$$

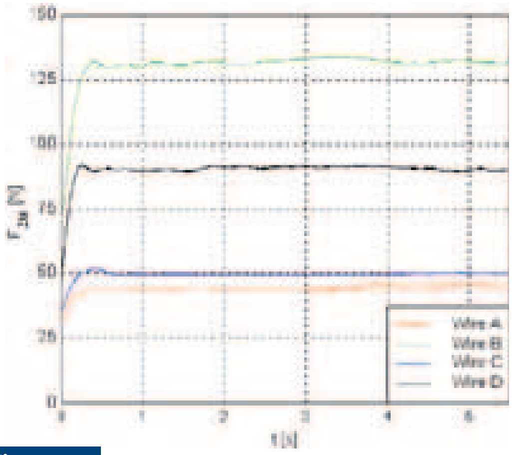


Fig. 5

Measured tensile forces

The product of the reference values for the bending moment and bend is defined according to Equation 14 for the circular cross section.

$$M_p \cdot \kappa_p = \frac{R_p^{\,2} \cdot \pi \cdot d^2}{16 \cdot E} \qquad \text{Eq. 14}$$

Verification

Simulation calculations [5] were carried out for the straightening unit according to Table **1** and for the selected wires (Table **2**). The calculated reference adjustment-related bends of the process material κ^*_{iv} and the adjustments a_i are summarized in Table **3** for the bending operations i performed. The total tensile force requirement F_{ZR} is derived by adding the tensile force components F_{iZR} of the respective bending operations documented in Table **3**, which were calculated using the above model.

The calculated results were verified by comparison with the measured tensile forces. This entailed setting the simulated adjustments a_i [5] on the straightening unit starting from the respective wire-specific zero line and measuring the total tensile force by sensor. Five tests were performed for each of the wires selected. Fig. **5** shows the characteristic tensile force/time curves for an exemplary selection of the wire data sets. The level of tensile force was derived by evaluating a tensile force/time curve on the basis of ANSI/IEEE 194-1977. Table **4** shows an overview of the tensile forces F_{ZMv} determined by experiment and lists the mean values and corresponding standard errors of the total tensile force .

The quality of the model for determining the tensile force requirement is expressed by the relative error ε_r of the calculated results in relation to the measured results, which for wire A is $\varepsilon_r = 4\%$, for wire B is $\varepsilon_r = 5\%$, for wire C is $\varepsilon_r = -2\%$ and for wire D is $\varepsilon_r = 0\%$.

Summary

The calculation specifications [3, 4] recommended for determining the tensile force requirement for straightening with roller-type straightening systems supply – in comparison with the measured results – only rough approximations that are no longer appropriate for the optimized planning and design of straightening systems on the one hand and of the machinery and apparatus in which such straightening units are integrated on the other hand. A new model for calculating the tensile force requirement was developed selectively on the basis of a requirements profile. It takes account for the first time of the straightening unit's geometrical boundary conditions such as number of rollers, roller diameter, roller profile and pitch, as well as the properties of the process material such as its geometrical and material data, whereby the adjustments can be made at random and with any method. Key elements of the model are the numerical determination of the bending moment/bend curves for the bending operations performed in the straightening unit and hence the possibility of determining the work of plastic deformation, which correlates with the tensile force requirement in accordance with the energy balance. Calculations carried out for an exemplary selection of wires using the new model display a very good correlation with the measured values. The model's future use in the wire industry is thus possible.

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