Inline wire diagnosis

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Abstract

Wire yield point and diameter consistency are important parameters determining the final geometry of bending parts and springs. This paper introduces recent ideas and the results of trial runs for monitoring changes of these parameters during wire drawing. The so-called "inline wire diagnosis" represents a new system for classifying wire quality based on seamless verification, and allows a continuous and objective intrinsic quality assessment.

Motivation

The production of wire is defined worldwide by two parameters: quality and quantity. Quantity can be achieved simply with a high number of drawing machines and a high drawing speed. Quality and the production process depend significantly on the properties of the process material and require coordinated production equipment, dies and media. In particular the geometrical and mechanical properties of the wire and its tolerances over its length have a strong impact. Unlike quantity, there is nothing simple about producing quality.

High-tech wire and its products are subject to high requirements in terms of reject rate and achieving a defined geometry. The only way to influence these parameters positively is with properties which are constant over the wire's length. In practice, constant properties over length are verifiable only with limitations. On wire drawing machines, for example, only the wire diameter might typically be monitored continuously.

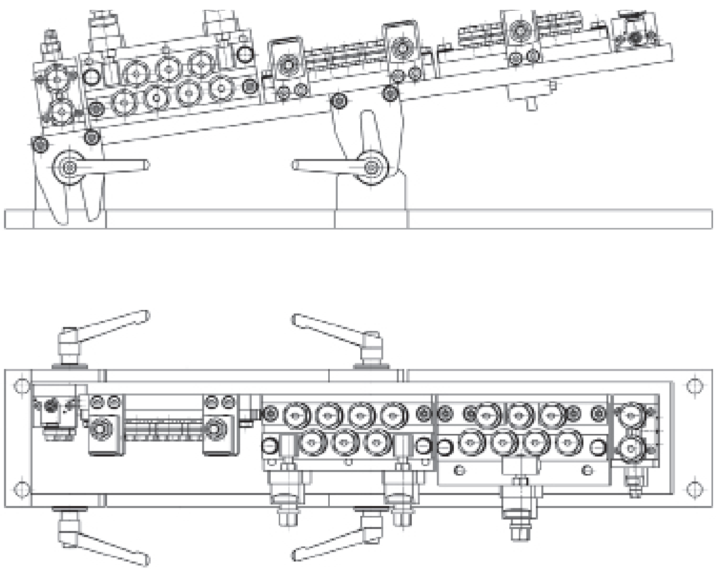
As for the wire's mechanical properties, directives specify quantitative parameters which must be determined after the wire drawing process by discontinuous and destructive means in tensile tests according to DIN EN 10002. The state-of-the-art is to perform the tensile test on up to five wire offcuts or samples. The results of the tensile test are then regarded as representative of the entire reel or the entire coil and are presented to the customer or wire processor in the form of a certificate.

With 'inline wire diagnosis' it is aimed to provide an alternative certificate based on the continuous and non-destructive determination and documentation of changes to a wire's strength over its length. Here the focus is not on a change of tensile strength Rm, which in various standards concerning the terms of delivery for long products is considered as the only relevant tension parameter, but on a change of the technical yield point $R_{p0.2}$. A change of the technical yield point is more important than tensile strength for technical and commercial objectives because it is decisive for the elastic-plastic forming processes which follow the wire drawing process.

Process

The structure of the 'inline wire diagnosis' process has two levels. On a preparatory level, a process simulator uses mathematical-physical models to simulate a forming process[1]. The process simulator carries out a variation calculation, which in effect is a repeat performance of a simulation calculation. Each simulation calculation is carried out with different discrete values of the variation parameters. The variation parameters are the wire diameter d and the technical yield point $R_{p0.2}$, ie the target values of the 'inline wire diagnosis'.

Using the nominal value of the wire diameter and the nominal value of the technical yield point as reference, the variation limits of the variation parameters are defined by the

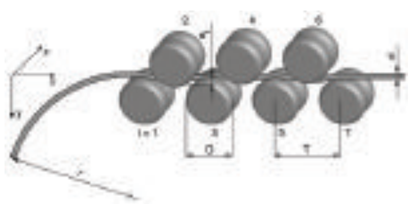


▲ *Fig 1: Straightening system and diagnosis unit* permissible deviations according to the relevant directive or the relevant terms of delivery. Spring steel wire, for example, is governed by the directive DIN EN 10270-1. Each simulation calculation considers not only the data of the wire process material but also the geometrical data of a diagnosis unit which is similar in layout to a roll straightening unit. Other physical elements of the process are a straightening system upstream from the diagnosis unit (Fig 1) and a device for identifying the wire diameter.

The straightening units of the straightening system and the diagnosis unit use rolls with defined adjustability as tools for configuring the straightening processes and for configuring the diagnosis process. Fig 2 presents a number of the wire's geometrical parameters and shows by way of example the parameters of those physical elements of the process which are equipped with rolls. The adjustment ai of the rolls i (I = 1-7) during the wire's pass, subjects it to elastic-plastic alternating deformations which are the basis for the change of the wire's geometrical parameters and also the basis for the diagnosis of the wire over its length. Each roll-equipped physical element of the process has an identical straightening or deformation range △ which is defined by the pitch T (the distance between the rolls) and the diameter of the rolls D (Fig 2).

In accordance with this data, the straightening and deformation range has a permissible limit for the minimum wire diameter d_{min} and the maximum wire diameter d_{max} to be processed (equation 1).

$d_{min} \leq \triangle \leq d_{max}$ Equation 1

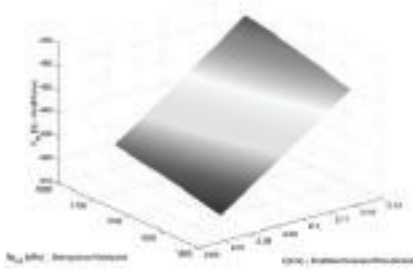


▲ *Fig 2: Physical element of the process with parameters*

Given straightening units with a process-compatible configuration and a diagnosis unit with a process compatible configuration, then the deformation processes will be defined by the reciprocal value of the curvature radius r or the curvature and material properties of the wire at specified actual values of the wire diameter and the technical yield point. Any impact of the curvature in the diagnosis unit is ruled out by a special adjustment method or early smoothing of the wire curvature[2] in the straightening system upstream from the diagnosis unit. For the diagnosis unit this results in a relationship between the parameters of the wire and the target values of the inline wire diagnosis (diameter, technical yield point) and the diagnosis process parameter roll force F_{Ri}[3] which, uninfluenced by the curvature, is mapped by a relationship matrix as the result of the variation calculation.

Fig 3 presents by way of example a relationship matrix for a bezinal wire of grade SH with nominal diameter d_N = 2.1mm and nominal yield point $R_{p0.2N}$ = 1700MPa. The variation limits of the variation parameters are defined in accordance with directive DIN EN 10270-1 with equation 2 and 3.

$2.075 \leq d_N \leq 2.125$ mm Equation 2
$1625 \leq R_{p0.2N} \leq 1775$ MPa Equation 3



▲ *Fig 3: Relationship matrix as a result of the variation calculation*

The information content of the relationship matrix describes for discrete values of the variation parameters the relationship to the diagnosis process parameter roll force. Using the data of the relationship matrix, a functional relationship is derived on the process preparation level with the help of assessment statistics methods. For the dependence documented in Fig 3 there are the three random variables x_1, x_2 and y. The parameters a, b_1 and b_2 in equation 4 are estimated by multiple linear regression.

$y = a + b_1 \bullet x_1 + b_2 \bullet x_2$ Equation 4

For the estimation it is aimed to achieve a good adjustment to all the values of the random variable y. The quality of the adjustment is reflected by the degree of determination B. The closer the degree of determination to the value 1, the greater the conformance between y and € Equation 5 describes the estimation for the example according to equation 2 and 3 and Fig 3.

$R_{p0.2} = 191688 - 11355 \cdot d + 14.4777 \cdot F_{Ri}$ B = 0.9881 Equation 5

On the implementation level of the process, the actual value of the wire diameter and the measured roll force thus result in the estimated value for the technical yield point $R_{p0.2}$. A continuous and non-destructive estimation of the technical yield point over the wire's length is achieved accordingly from continuous identification of the wire diameter and the roll force.

Static tests, which are performed as part of a verification process and indicate a relative error of ±3%, document the quality of the process simulator. The error is determined from the expected value of the roll force from the simulation on the one hand and from the exact value of the roll force or the measured roller force on the other hand.

Test run

The implementation level uses a program whose user interface is shown in Fig 4. Measured parameters, eg the wire diameter and roll force, and the estimated value of the technical yield point and the wire speed are presented in the form of a table and a diagram. All data are saved in TDMS format together with verbal notes on the project.

The test run is performed at a wire speed of 5.8m/s for four finished reels on a Bekaert dry drawing machine under production conditions. The straightening system and the diagnosis unit are installed in the area of the last drawing machine block. The wire passes from the lower capstan of the last block through the straightening system and the diagnosis unit to a deflector roller which deflects the wire onto the upper capstan.

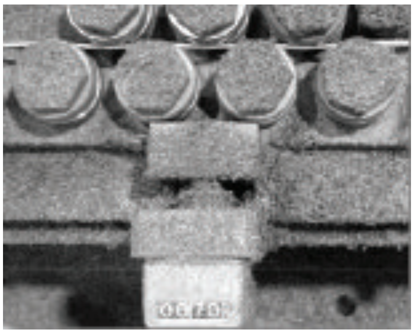
Directly after the upper capstan the wire passes through the unit for identifying the wire diameter. The offset between the diagnosis unit and the diameter measuring device is defined and taken into account by the inline wire diagnosis. The running direction of the wire from left to right (Fig 1) enables the roll force to be measured in the diagnosis unit on the discharge side. The measuring frequency for all the previously mentioned parameters and variables equals 5kHz.

The rolls of the straightening system and the diagnosis unit are set with defined adjustments for the elastic-plastic deformation of the wire (Fig 5). The adjustment of the rolls in

▲ *Fig 4: User interface of the inline wire diagnosis program*

the diagnosis unit corresponds to 1.4 times the maximum elastic adjustment. This goes hand in hand with an only small change of wire curvature through deformations in the diagnosis unit, which is changed by a downstream straightening system into the desired constant residual curvature.

Fig 6 shows by way of example the characteristic curve of the parameters and variables as a function of time or wire length. During the acceleration and deceleration of the wire, the roll force displays high dynamics. This is caused by a non-constant difference in force between the drawing force and the back pull force during the acceleration and deceleration phase. It can be influenced by the drawing machine design, the drawing machine control system, the control parameters and the drawing process

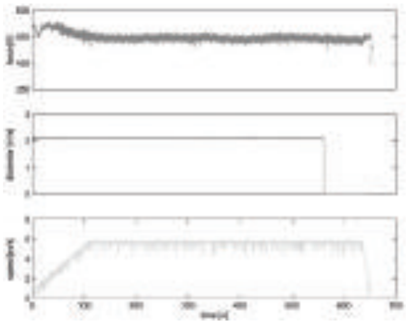


▲ *Fig 5: Elastic-plastic deformation of the wire in the diagnosis unit*

configuration. For example, higher numbers of turns on the lower and upper capstan will help to improve the constancy of the difference in force between drawing and back pull force, which will also be reflected in the time-related characteristic curve of the wire speed. Between the acceleration and deceleration phase, the roll force has a characteristic curve which can be used for the inline wire diagnosis. Like the roll force, the wire diameter also displays high dynamics in the area of the acceleration and deceleration phase. The causes are unknown and need to be discussed. They cannot be derived from the laser measuring principle. For this reason it should be noted that the quality of diameter measurement is hardly adaptable to the requirements of dry wire drawing under production conditions.

Wire vibrations and, above all, dirt deposits formed from eg drawing soap and coating chips have a negative effect on inline measurement of the diameter. As can be seen in Fig 6, the dirt accumulations soon cause the diameter measurement signal to show fail. The splashguard and air curtain provided by the manufacturer of the diameter measuring device do not produce an improvement which leads to a permanently reliable signal. Certainly, the maintenance recommended by the manufacturer – namely regular cleaning of the measuring windows – does help to enable the temporary use of the device, but maintenance intervals of five minutes are hardly viable for the operator of a drawing machine.

In view of these disadvantageous boundary conditions, the inline wire diagnosis test run is restricted to a time and wire zone which is not only uninfluenced by the wire acceleration and deceleration but also based on a plausible diameter measuring signal. On the implementation level of the inline wire diagnosis, the characteristic curves of the roll force and diameter presented in Fig 6 result in a characteristic curve of the technical yield point in accordance with Fig 7. The area of the estimated value of the yield point which is highlighted in black has been evaluated and results in the assigned histogram. The standard deviation and the median of the technical yield point can be used to evaluate the wire and to compare projects or wire reels.

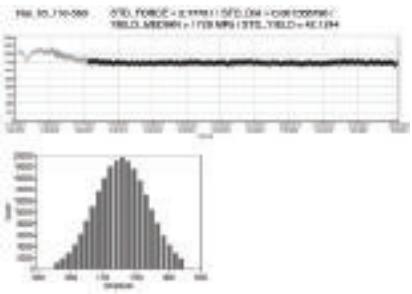


▲ *Fig 6: Measured values of the roll force, diameter and speed of the wire*

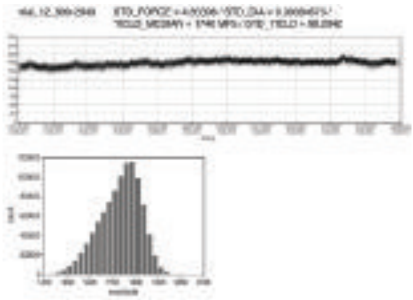
The projects or wire reels are classified on the basis of the standard deviation of the estimated value of the technical yield point and assigned to one of the following arbitrary defined quality grades: VERY GOOD, GOOD, SATISFACTORY, ADEQUATE or POOR. The class limits are illustrated by the equations 6 to 10.

40 ≤ VERY GOOD < 50 MPa	**Equation 6**
50 ≤ GOOD < 60 MPa	**Equation 7**
60 ≤ SATISFACTORY < 70 MPa	**Equation 8**
70 ≤ ADEQUATE < 80 MPa	**Equation 9**
80 ≤ POOR ≤ 90 MPa	**Equation 10**

Accordingly, project #18 in Fig 7 reflects a very good constancy of the technical yield point while project #12 in Fig 8 indicates a poor level of wire quality. The standard deviation of the technical yield point in project #12 is approximately 109% greater. This is owed to accordingly large standard deviations of the wire diameter and the roll force, which in project #12 are approximately 200% and approximately 75% greater than in project #18.



▲ *Fig 7: Time-related characteristic and histogram of the yield point for project 18 (finished reel 4/1)*



▲ *Fig 8: Time-related characteristic and histogram of the yield point for project 12 (finished reel 2/1)*

To assess the plausibility of the time-related characteristic of the wire diameter and the estimated value of the technical yield point, the wire diameter is measured and tensile tests in accordance with DIN EN 10002 are performed after the test run on select wire sections of the projects and finished reels. Table 1 presents the results of the inline wire diagnosis test run along with the results of the wire diameter measurements and the tensile tests.

Project/ Reel/	BEKAERT		WITELS-ALBERT & BEKAERT					
	d [mm]	$R_{p0.2}$ [MPa]	MEDIAN d [mm]	STD d [mm]	MEDIAN F_m [N]	STD F_m [N]	MEDIAN $R_{p0.2}$ [MPa]	STD $R_{p0.2}$ [MPa]
#10/#1/1	2.099	1704	2.114	0.0052	445.7	3.51	1630	70.4
#11/#1/2	2.099	1694	2.111	0.0044	448.8	4.10	1680	75.1
#12/#2/1	2.098	1716	2.111	0.0039	453.9	4.88	1746	88.2
#14/#3/1	2.095	1699	2.109	0.0047	451.0	3.40	1737	69.9
#15/#3/2	2.094	1733	2.111	0.0028	466.0	2.54	1928	50.3
#18/#4/1	2.097	1688	2.105	0.0013	448.8	2.78	1729	42.1
#19/#4/2	2.100	1693	2.106	0.0019	448.0	2.73	1742	42.8

▲ *Table 1: Tensile test (Bekaert) versus inline wire diagnosis (Witels-Albert and Bekaert)*

The wire diameter determined on the wire sections before the tensile tests lies below the respective median of the wire diameter which results from the inline wire diagnosis. The results of the test run are largely confirmed by the results of the tensile test, which in all cases satisfy the directive DIN EN 10270-1. Only in project #15 (finished reel #3/2) is the technical yield point determined with the inline wire diagnosis distinctly greater than the comparative value from the tensile test. The reasons for this and for the large spectrum of standard deviations of the technical yield point from the inline wire diagnosis could not be sufficiently identified in the context of the test run. It is thought that the drawing machine and the drawing process as well as specific states of the drawing machine and the drawing process may have an influence. For example, there is a correlation between the results of the project #15 (finished reel #3/2) and a significant increase in the tensile strength as a result of a temporarily blocked capstan cooling. In this connection it should be pointed out that the purpose of the inline wire diagnosis is not to determine the actual technical yield point but to identify changes in the technical yield point.

Conclusion

With the test stations available to the research group (developed by them) and the newly developed experimental hardening and tempering plant, it has for the first time become possible to imitate in the laboratory all the heat treatment procedures from the wire works to the finished spring, using completely independent parameter variation, and then to improve the springs' strength properties.

The research group is thus in a position to find the optimum tempering processes for other wire products and provide industry with the results, all without high expenditure of time and money. Thus, conclusions can be drawn for the design and operation of new passage tempering plants to be used in wire manufacture and for the selection of process parameters at the spring tempering stage.

The knowledge obtained (to the effect that heat treatment processes calculated in combination for wire and spring manufacture will enable shaping and strength properties to be specifically improved) is promising for improved manufacture and more accurate dimensioning of heavily loaded springs. It was proved that the hardening and tempering parameters have varying effects on yield points and ultimate tensile strength. The nominal value for the yield point under torsional stress $T_{t\ zul}$ which is particularly important for the materials used in helical compression springs can be increased by up to 10% by optimally tuned wire hardening and component tempering parameters.

It is fundamentally possible to achieve reduction of maximum strength of the material to improve capacity for coiling after the wire works and then to set the desired high strength levels during the manufacture of the spring. It was also made clear that static and dynamic strength cannot be optimised simultaneously but that the heat treatment must be set at all stages to meet the use to which the spring is to be put.

References

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[3] Paech, M: Advanced semi-automatic straightening technology. Wire Journal International, July 2008, pp 74-79