

Inline wire diagnosis

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 their tolerances over its length have a strong impact. Unlike quantity, there is nothing simple about producing quality!

By Marcus Paech and Walther Van Raemdonck

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 being 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 the 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 R_m , 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 process¹. 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 $R_{p0.2}$, i.e. 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 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.

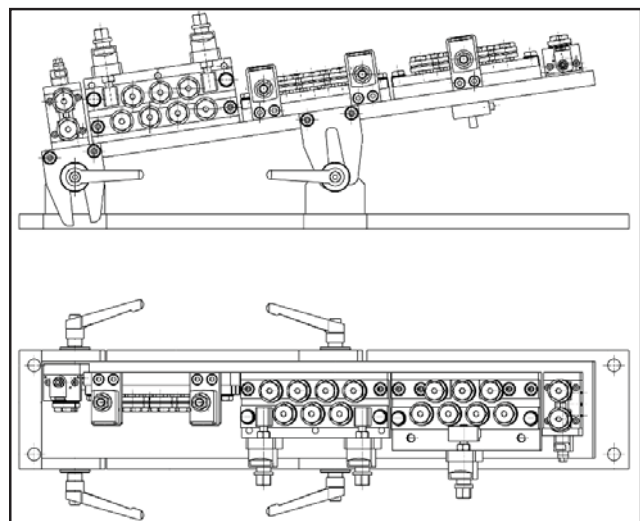


Fig. 1. Straightening system and diagnosis unit.

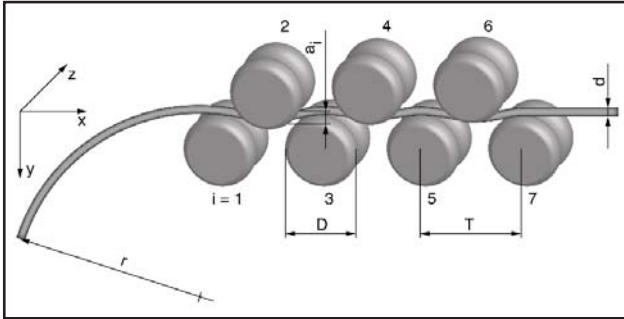


Fig. 2. Physical element of the process with parameters.

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 a_i 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 Δ which is defined by the pitch T (the distance between the rolls) and the diameter of the rolls D . See Fig. 2.

In accordance with these 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.

$$d_{min} \leq \Delta \leq d_{max} \quad (\text{Eq. 1})$$

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 curvature² 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 FRi 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 $d_N = 2.1$ mm and nominal yield point $R_{p0.2N} = 1700$ MPa. The variation limits of the variation parameters are defined in accordance with directive DIN EN 10270-1 with equation 2 and 3.

$$2.075 \leq d_N \leq 2.125 \text{ mm} \quad (\text{Eq. 2})$$

$$1625 \leq R_{p0.2N} \leq 1775 \text{ MPa} \quad (\text{Eq. 3})$$

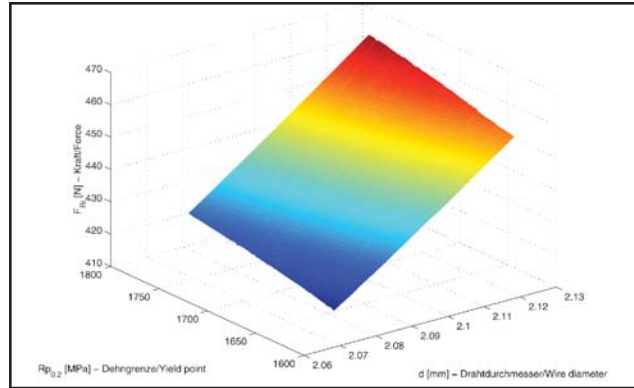


Fig. 3. Relationship matrix as a result of the variation calculation.

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.

$$\hat{y} = a + b_1 \cdot x_1 + b_2 \cdot x_2 \quad (\text{Eq. 4})$$

For the estimation \hat{y} 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 \hat{y} . Eq. 5 describes the estimation for the example according to equation 2 and 3 and Fig. 3.

$$\begin{aligned} \hat{R}_{p0.2} &= 191688 - 11355 \cdot d + 14.4777 \cdot FRi \\ B &= 0.9881 \end{aligned} \quad (\text{Eq. 5})$$

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 $\hat{R}_{p0.2}$. 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 $\pm 3\%$, 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, e.g. the wire diameter and roll force, and the estimated value of the technical yield point and the wire speed are presented

is hardly adaptable to the requirements of dry wire drawing under production conditions.

Wire vibrations and above all dirt deposits formed from e.g. 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 signal fail. The splash guard 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.

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.

- $40 \leq \text{VERY GOOD} < 50 \text{ MPa}''$ (Eq. 6)
- $50 \leq \text{GOOD} < 60 \text{ MPa}''$ (Eq. 7)
- $60 \leq \text{SATISFACTORY} < 70 \text{ MPa}''$ (Eq. 8)
- $70 \leq \text{ADEQUATE} < 80 \text{ MPa}''$ (Eq. 9)
- $80 \leq \text{POOR} \leq 90 \text{ MPa}''$ (Eq. 10)

Accordingly, project #18 in Fig. 7 reflects a very good constancy of the technical yield point while project #12

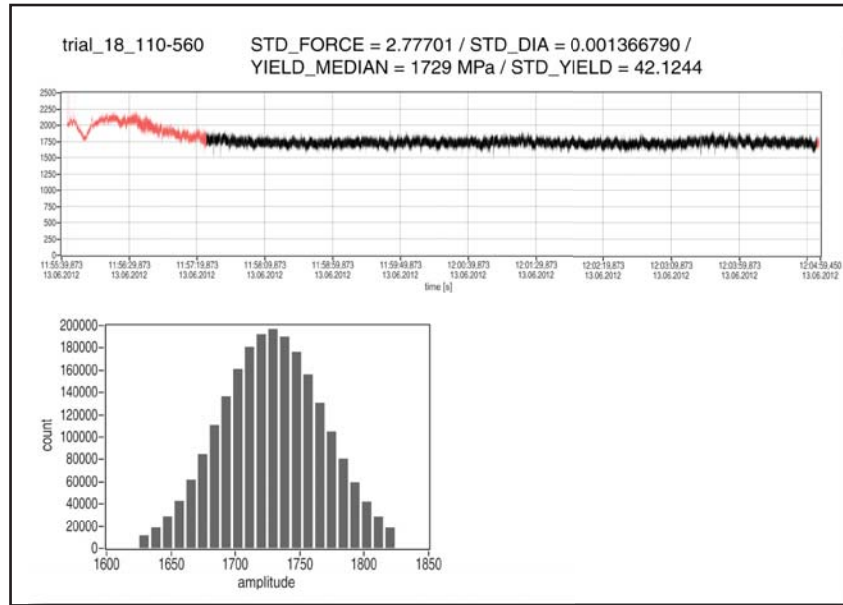


Fig. 7. Time-related characteristic and histogram of the yield point for project #18 (finished reel #4/1).

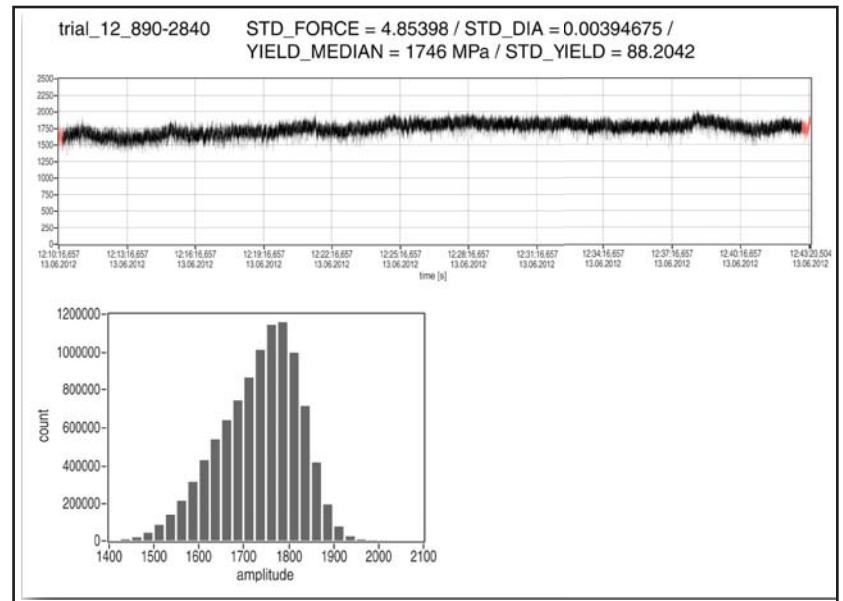


Fig. 8. Time-related characteristic and histogram of the yield point for project #12 (finished reel 2/1).

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

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

Project/ Reel/	BEKAERT		WITELS-ALBERT & BEKAERT					
	d [mm]	Rp0.2 [MPa]	MEDIAN d [mm]	STD d [mm]	MEDIAN FRi [N]	STD FRi [N]	MEDIAN Rp0.2 [MPa]	STD Rp0.2 [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	4.86	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	465.6	2.54	1928	50.3
#18/#4/1	2.097	1686	2.105	0.0013	446.6	2.78	1729	42.1
#19/#4/2	2.100	1693	2.106	0.0019	448.0	2.73	1742	42.9

Table 1. Tensile test (Bekaert) versus Inline Wire Diagnosis (Witels-Albert & Bekaert).

the Inline Wire Diagnosis test run along with the results of the wire diameter measurements and the tensile tests.

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

The Inline Wire Diagnosis is designed to determine changes of the technical yield point. It is based on identifying the wire diameter, on measuring the roll force, and on relevant mechanical laws of the model of the three-fold statically undefined bend, which is assumed to be valid for the deformation process performed with a diagnosis unit.

The project contributes to the assessment and adjustment of a wire product's quality. The continuous availability of information about changes in the wire's diameter and the technical yield point creates a new system of values for the classification of wire grades, which focuses on permanently determining the constancy of these properties and their correlating technical and economic aspects. For users such as wire drawing or processing companies, this opens up the innovative possibility of marketing their products on the basis of a consistently verifiable quality and of adjusting the quality selectively and continuously, e.g. through their choice of tools, the control system of the drawing or processing machine, the control parameters, and the configuration of the drawing or processing process.

Further studies will consider how to increase the robustness of the Inline Wire Diagnosis, in particular the need to reduce the influence of the non-constant difference in force between the drawing and backpull force. The results obtained so far indicate that both the identification of the roll force and the identification of the wire diameter are influenced by the non-constant difference in force between the drawing and backpull force.

If the need for the Inline Wire Diagnosis is questioned, then so must that of diameter measurement: the difference in the standard deviation of the wire diameter are significantly higher than the differences in the standard deviation of the roll force. In this connection it should be asked why the contactless measurement of wire diameter has become so widespread, particularly considering that the results over the wire length are uncertain, are not continuously identified and documented, and are not made available in useful form for subsequent processes.

Further studies are concerned with the influence of adjustments to the rolls of the straightening system and to the rolls of the diagnosis unit. It is very likely that roll adjustments which affect a greater elastic-plastic deformation of the wire lead to an increase in the robustness of the Inline Wire Diagnosis and to a reduction of the influence of the non-constant difference in force between the drawing and backpull force. It is proposed to increase the adjustment of the rolls of the diagnosis unit step by step to double the maximum elastic adjustment. An accordingly modified diagnosis unit is used in parallel to measure the transport force in the wire passing direction and to assess the static relationship to the roll force. The empirical covariance and the correlation coefficient will qualify indications of the correlation between the forces and specific roll adjustments for the straightening system and for the diagnosis unit for the Inline Wire Diagnosis. Further wire materials and wire grades must be investigated in addition in an extended test run. Alternatives to the contactless measurement of wire diameter are being considered.

Finally, the authors would like to point out that they look on the exchange of information on the process material wire as a major element of the new, knowledge-based wire industry. The path to a more open phase of cooperation needs to be laid for the sustained development of the wire industry. Although more efforts have to be spent to make the Inline Wire Diagnosis more robust and the interpretation more reliable, the authors are convinced that the process of the Inline Wire Diagnosis is a promising tool to monitor the consistency of drawn wire mechanical properties, helping to fine tune the processing and to better understand the intrinsic material characteristics. ■

Literature

1. W. Guericke, M. Paech, and E. Albert, "Simulation of the wire straightening process," *Wire Industry*, 8, 1996, pp. 613-620.
2. Paech, M. "Roller straightening process and peripherals," *Wire*, 51, 2001, 2, pp. 76-82.
3. M. Paech, "Advanced semi-automatic straightening technology," *Wire Journal International*, July 2008, pp. 74-79.



Paech



Van Raemdonck

Marcus Paech is technical managing director at Witels-Albert GmbH, Berlin, Germany, a position he has held since 2002. Prior to that he was research and development manager. He previously was a member of the scientific staff in the department of machinery and drive engineering at Otto von Guericke University of Magdeburg, Germany. He studied engineering at Otto von Guericke University of Magdeburg. Walther Van Raemdonck has been senior technology manager global processes in the Applied Technology and Manufacturing Department of NV Bekaert SA, Zvevegem, Belgium, since 2012. He joined the company in 1986 and has since been involved in numerous product and process development projects for steel cord and wire. He earned a PhD degree in metallurgy and applied materials science from

the Catholic University of Leuven, Belgium. This paper was presented at CabWire World Conference, Milan, Italy, Nov. 2013.