LONG-TERM STABILITY OF PATENTED COLD DRAWN STEEL WIRES

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ABSTRACT

In a recently completed research project 48 wires were prepared by varying the carbon content, type of smelting, type of patenting, chemical drawing preparation, single cross-section reduction and drawing speed. The paper gives an overview of:

- The changes of characteristic values for the mechanical properties determined by i.e. torsion and tensile tests during storage and depending on heat treatments
- An automated detection of cracks along the wire-length-surface (longitudinal cracks) which is based on the torsion-testing-curve
- And the correlation between the variation of wire strength parameters and the variation of geometry of springs and other components

Index Terms – steel-wires, long-term-behaviour, crack-detection

1. INTRODUCTION

The last two years have seen the “Wire and Spring” research group at Technische Universität Ilmenau cooperating with wire and spring manufacturers (in the form of the Eisendraht- und Stahldrahtvereinigung and the VDFI – the German spring manufacturers’ association) in a research project entitled “Long-term stability of mechanical parameters of patented drawn steel wire”. Natural ageing effects on (i.e. the long-term behaviour of) the mechanical parameters of patented drawn spring steel and rope wires were investigated in relation to a large number of initial and process parameter variables.

For the purpose, two types of Stelmor air-cooled rolled wire with 0.6 % or 0.8 % carbon and a diameter of d = 5.5 mm were produced from steel made with two different forms of steel smelting technology (electric-furnace and converter). As preparation for drawing, one portion of the rolled wires was simply pickled in a standing bath, the other was additionally patented in a lead bath. The wires patented in the lead bath where then subdivided and either pickled in a standing bath or a continuous pickling plant. The 12 rolled wires thus derived were shared between two wire drawing machines and there drawn in either 8 or 11 stages to a diameter of d = 2 mm. There were two drawing speeds, either 6 m/s or 12 m/s. The process resulted in 48 experimental wires of which the long-term stability was to be investigated. (Table 1 and Table 2)

Table 1: Variations set up in the wire production and drawing preparation

Rolled wire	**Rolled wire from converter steel**						**Rolled wire from electric furnace steel**					
Carbon content	C-content: 0,6%			C-content: 0,8%			C-content: 0,6%			C-content: 0,8%		
Patenting	Stelmor	lead bath		Stelmor	lead bath		Stelmor	lead bath		Stelmor	lead bath	
Chemical pretreatment	standing bath	standing bath	continuos pickling	standing bath	standing bath	continuos pickling	standing bath	standing bath	continuos pickling	standing bath	standing bath	continuos pickling
Rolled wire number	1	2	3	4	5	6	7	8	9	10	11	12

Table 2: Variations set up in the wire drawing experiments

Number of drawing stages	8 stages						11 stages					
Rolled wire number	1-6 (converter steel)			7-12 (electric furnace steel)			1-6 (converter steel)			7-12 (electric furnace steel)		
Drawing speed	slow 6m/s		fast 12m/s	slow 6m/s		fast 12m/s	slow 6m/s		fast 12m/s	slow 6m/s		fast 12m/s
Drawn wire number	1 - 12			25 - 36			13 - 24			37 - 48		

The first experimental step was to establish the mechanical parameters from tensile and torsional tests carried out shortly after the wires had been drawn. To document the change over time in these mechanical parameters, the same measurements were repeated after 2, 12, 28, 166 and 370 days. The wires were also subjected to heating in ways similar what could be expected in the further industrial processing of the material in question. The mechanical parameters were measured after all the heating episodes, and these tests were repeated after periods up to 8 months.

2. CHANGES IN CAHARACTERISTIC VALUES FOR THE MECHANICAL PROPERTIES

All these tests on the wire samples served, on the one hand, to confirm the relationships which are already known between the mechanical values and such factors as carbon content, patenting method, and so on. There were further facts established:

- The greater the increase in strength gained by a wire from heat treatment, the greater will be the age-related alterations to the properties of non-heat-treated wire. Tests on heat-treated wires make it possible to predict likely parameter changes due to time spent in storage. (cf. Figure 2 and Figure 3)
- As most components made of patented wires are submitted to heat treatment after manufacture, it makes sense to establish the nominal strength and yield values for the wires in their heat-treated state. (cf. Figure 1 to Figure 4)
- The increase in occurrence of longitudinal cracks during torsion tests after heat treatment of 150 °C–200 °C for 30 minutes is significant.
- No conclusions can be drawn from the values established in tensile tests as regards the torsion behaviour of the wires in helical springs. (compare Figure 2 with Figure 4)
- In this series of experiments, necking failure and number of twists, which are characteristic values for deformation, were not factors enabling any predictions to be made about alteration in wire ductility.
- In use of drawing machines with an increased number of drawing steps and/or more intensive cooling of the wires, there will be greater alteration of the characteristics with storage time or with heat treatment, respectively. Long storage may mean that the tensile strength ranges detailed in the standard fails to be met.

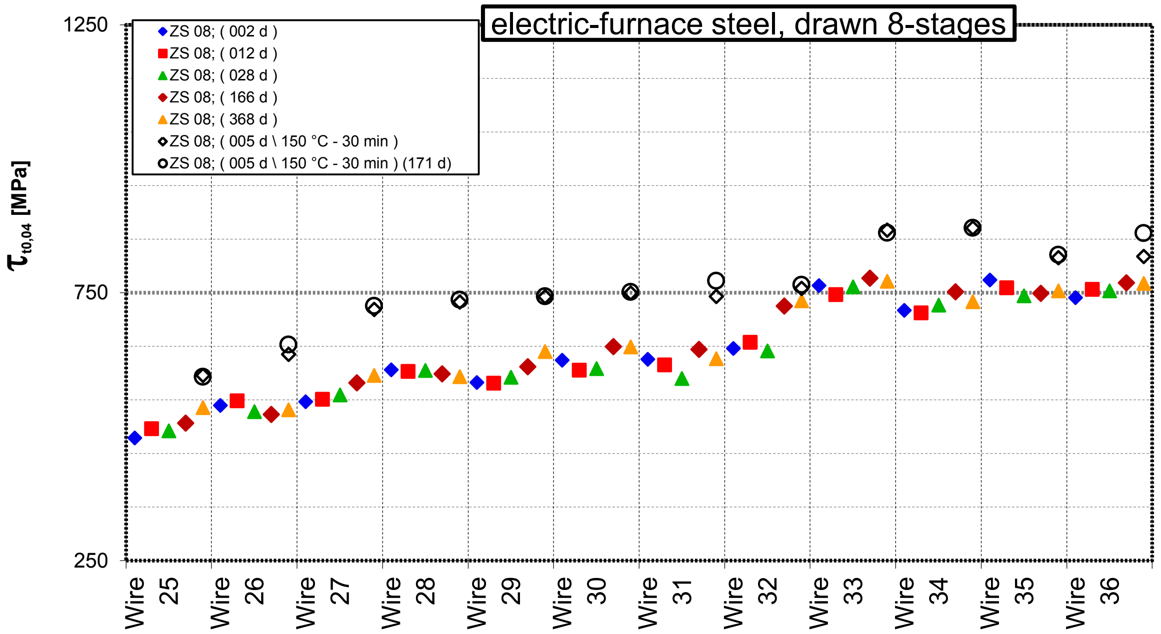


Figure 1: Torsion yield with 0.04 % residual strain under torsional stress τt0,04 after 2, 12, 28, 166 and 368 days following drawing of the wires and 5 days after drawing following heat treatment at 150 °C for 30 minutes

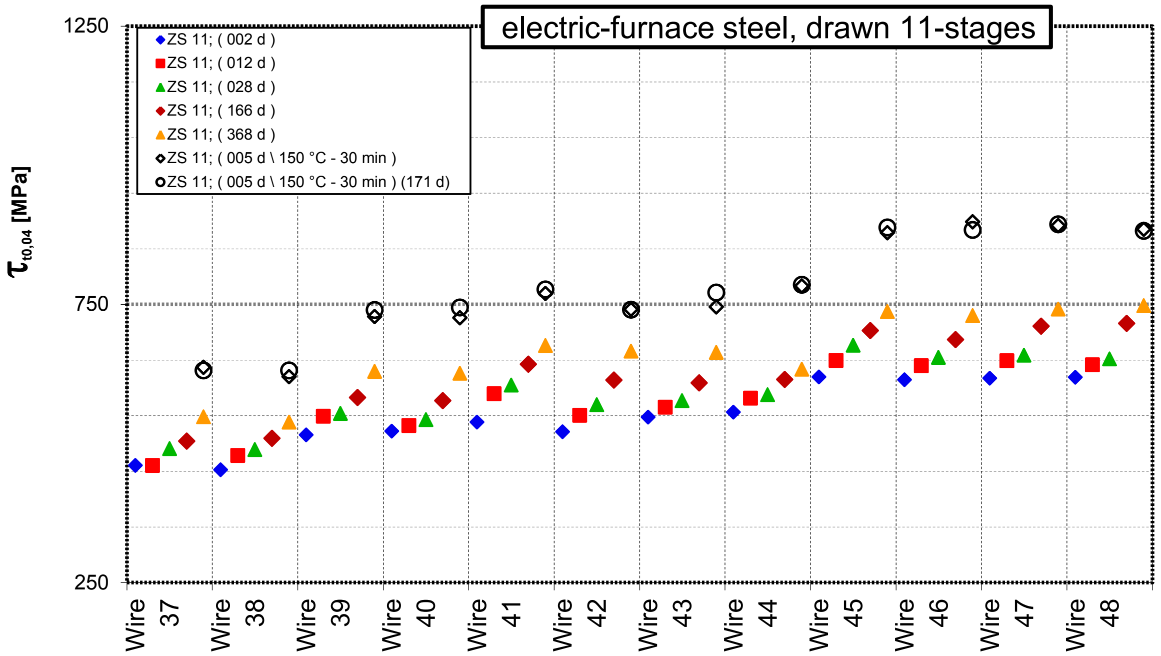


Figure 2: Torsion yield with 0.04 % residual strain under torsional stress τt0,04 after 2, 12, 28, 166 and 368 days following drawing of the wires and 5 days after drawing following heat treatment at 150 °C for 30 minutes

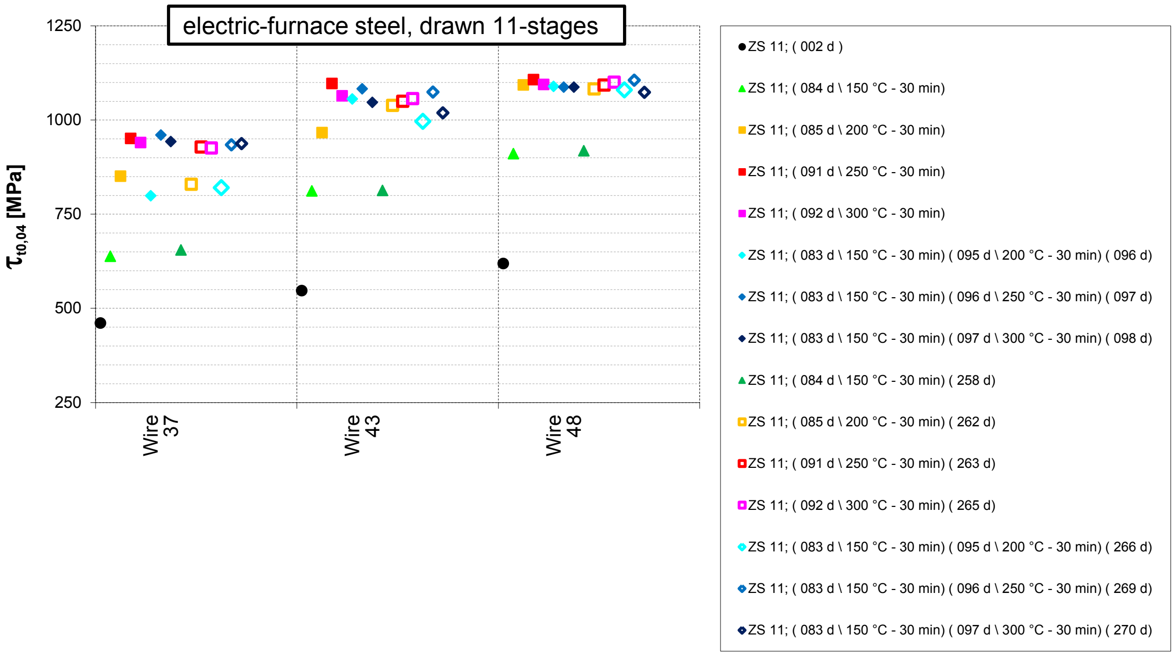


Figure 3: Torsion yield with 0.04 % residual strain under torsional stress τt0,04 with conditions varied for length of storage and heat treatment

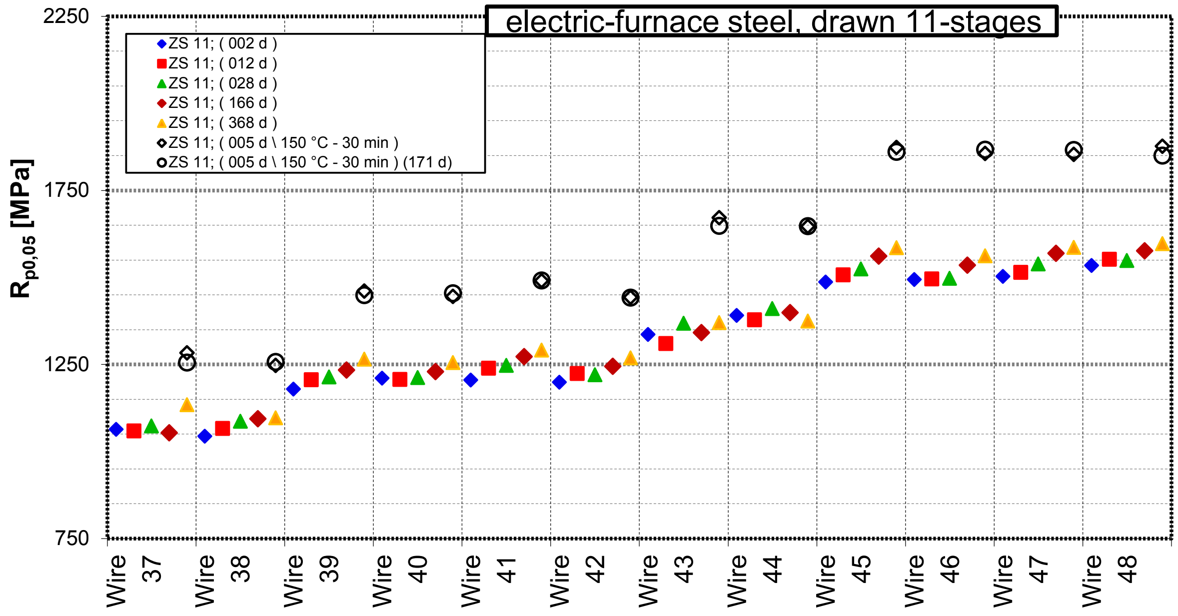


Figure 4: Stress-strain limit Rp0,05 after 2, 12, 28,166 and 368 days following drawing of the wires and 5 days after drawing with immediate heat treatment at 150 °C for 30 minutes

3. AN AUTOMATED DETECTION OF LONGITUDINAL CRACKS ALONG THE WIRE_LENGTH WHICH IS BASED ON THE TORSION-TESTING-CURVE

To establish the ductility of patented drawn steel wires it is usual to use the simple torsion test, which entails twisting a fixed length of wire until it breaks. A significant feature of wires which are limited in their plasticity is the development of longitudinal cracks, called torsion cracks in the literature (this is crack type 3 in Figure 5). More of them are also found after the wire has been heat-treated between 150 °C and 300 °C. This is the conventional temperature range for the tempering of springs and shaped wire parts after they have been manufactured (cf. Section 2). The surface of a wire with good plastic properties should be smooth after the torsion test and the fracture should be at right angles to the wire axis (crack type 1 in Figure 5). [2].

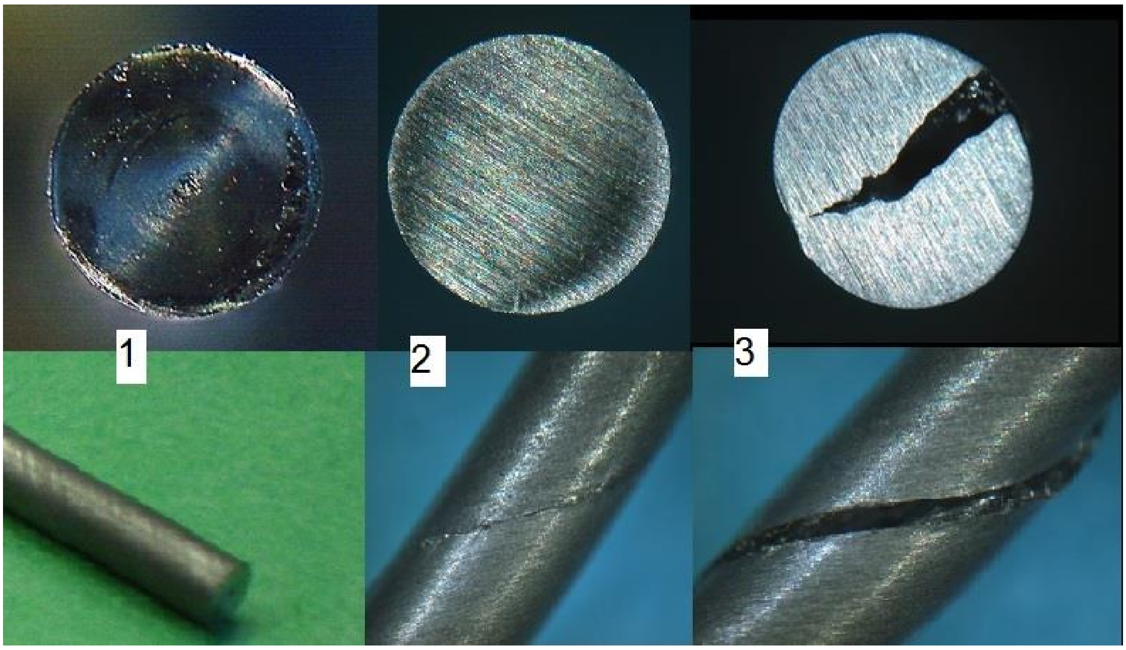


Figure 5: Crack types

During the torsion tests (with measurement of the torsion-angle and torsion-moment) on the 48 sample wires it was found that there were also intermediate stages in the fractures described in [2]. Disregarding certain mixed forms and fractures from recoil, these fractures can be roughly categorised into three types. As Figure 5 shows, the distinctions are

- crack type 1: no longitudinal crack, “normal torsional fracture”, Smooth – Fracture plane perpendicular to wire axis (or slightly oblique). No cracks in fracture plane (1a according to EN 10218-1[1]);
- crack type 2: longitudinal crack is not along the whole wire axis, “fracture with local cracks”, Smooth – Fracture plane perpendicular to wire axis and partially cracked (roughly 2a according to EN 10218-1[1])
- crack type 3: complete longitudinal crack along the wire axis, “fracture with cracks along the entire length”, Smooth – Fracture plane perpendicular to wire axis and partially cracked (3a according to EN 10218-1[1])
- crack type 3*: longitudinal cracks distributed irregularly over the length of the wire, fracture plane parallel to the wire axis in parts

If one compares the graph for stress / strain under torsional stress (curve from the torsion test on wires) with these different types of cracks (Figure 6), it can be seen that in the case of all wires that do not have the normal torsional fracture represented by 1a in EN 10218-1, the torsion stress first increases up to an initial peak, then falls abruptly. When the torsion stress has fallen, the wires (with cracks of type 2 and 3) start to become strong again and achieve a further maximum of torsion stress. It is after this that the fracture occurs. Only in the case of wires with type 3* cracks is there no further strengthening, i.e. no further peak in the torsion testing curve. However, even in the case of wires with this type of crack, the crack can be recognised clearly from the torsion testing curve.

The significance of this is that it is possible to recognise a crack simply by examining the torsion testing curve. However, it should be noted that the curve does not give any indication of whether the fracture plane can be classified as being at right angles to the axis.

A search was made for one characteristic as an objective and automated means of evaluating the cracks using the torsion testing curve; the value for this characteristic should permit evaluation of the wire in respect of probable cracks without further close examination of the curve. In the course of the search the total strain under torsional stress in the torsion test was related mathematically to the distance travelled in one traverse of the measuring machine so as to keep the tensile stress constant in the torsion-test (the quotient between total strain under torsional stress and traverse distance was found) (Figure 7). For wire that does not crack (crack type 1 in Figure 5), this quotient is approximately -0.05, for wire that cracks partially it is approx. -0.10 and for wire cracking along the complete length it is -0.25. These are the values for wires of diameter d = 2 mm, length under stress of 300 mm, as found with the instruments at the research centre.

A second step is a novel evaluation of the torsion tests. By this means, it is possible to detect cracks directly in the graph of stress plotted against strain under torsional stress by establishing the maximum torsional stress on cracking and the strain (under torsional stress) on cracking (see Figure 8).

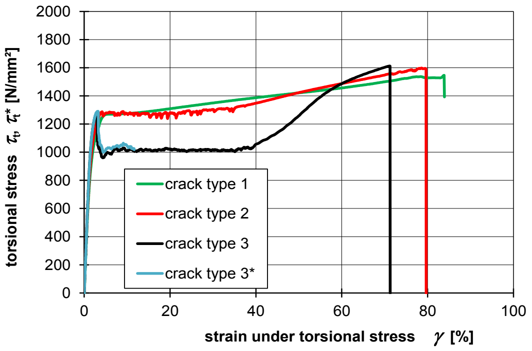


Figure 6: Graphs of stress against strain under torsional stress for crack types 1–3 from **figure 5**

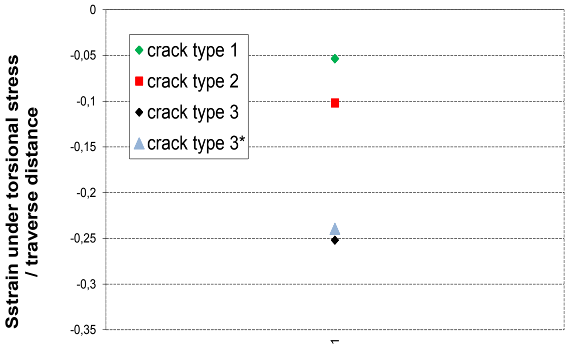


Figure 7: Quotient between strain under torsional stress and traverse distance

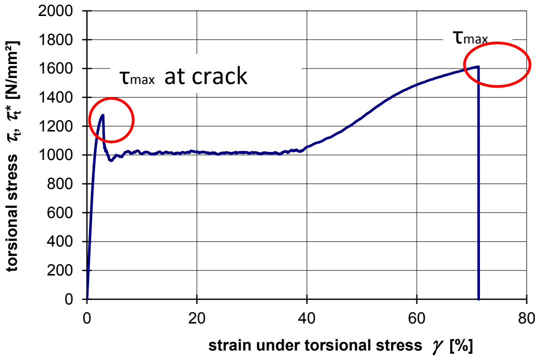


Figure 8: Comparison of maximum torsion stress on cracking and maximum torsion stress overall

4. THE CORRELATION BETWEEN THE VARIATION OF WIRE STRENGTH PARAMETERS AND THE VARIATION OF GEOMETRY OF SPRINGS AND OTHE COMPONENTS

When rolled wires are manufactured for the spring steel industry there are various speeds of cooling during the Stelmor air-patenting process for different sections of the wire. As with every steel product, the alterations in the crystalline structure of rolled wire are set by the speed of cooling and the length of time for which a temperature is maintained [3]. The variations in the cooling of the separate sections of wire will thus cause an inhomogeneous distribution of crystalline structure and thus less than satisfactory distribution of the strength in the wire.

For extremely-high quality products which require very high uniformity and strength, the rolled wire is given additional cost-intensive patenting in a continuous lead bath. However, to save money this step is often omitted from the process. It is now intended to shape the unpatented wire into a high-tech product with sophisticated geometrical and resilience requirements: the industrial spring. When springs are manufactured, for instance using an automatic coiling machine, the principle is to bend the wire in a defined space until it has passed its yield point. Any variation in strength of the spring steel wire will have an effect on the geometry at exactly this point. Varying strength along the wire axis, i.e. varying yield points, will cause deviations in the shape of the end product. Figure 9 demonstrates the point with two springs: in material that is irregular (wire 1 above) and uniform (wire 2 below). The extreme variations in coil diameter D of the spring section in the case of the non-uniform material can be clearly seen. The equation for the spring ratio (1) makes it clear that such diameter variations will affect the spring ratio to the power of three, which is, obviously, a considerable modification.

$$R=(G\cdot d^4)/(8\cdot D^3\cdot n) \qquad (1)$$

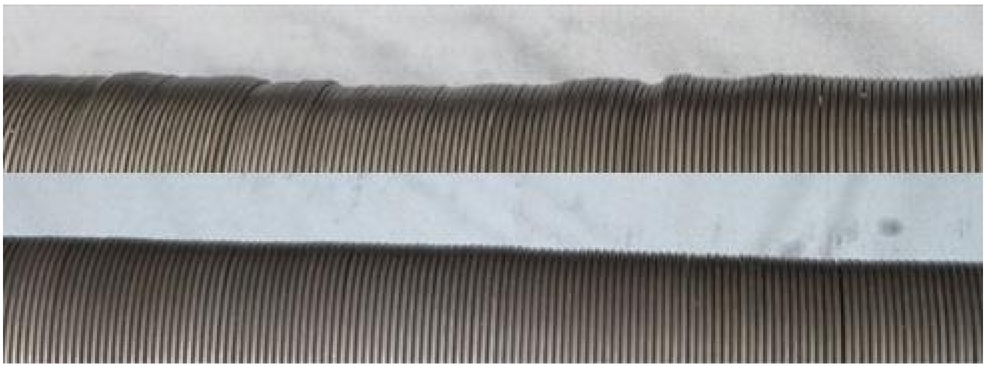


Figure 9: Comparison of two spring sections (“Wire 1” above; “Wire 2” below)

Even in the case of shaped wire parts or leg springs, variations in strength will play a significant role, for example influencing the angle between the two legs and thus often preventing automatic assembly of parts.

Conventional practice is currently only to test the tensile strength at the beginning and end of a wire coil. Absolute accuracy would only be possible if many tensile tests were made across an entire wire lot – but as wire is an “endless” product this is not practicable. To find out the variations in strength present in a wire, there is the time- and cost-intensive option of a high number of tensile tests on the wire (see Figure 10). What Figure 10 shows is the results from 50 tensile tests on two different wires, one very uniform and one very far from uniform. The samples were cut from the wire coil in the form of wire rings and then subjected to this series of tests. The range of tension in the case of “wire 2” was only about 30 MPa, while it was 160 MPa in the case of “wire 1”.

A different test of spring steel wire reflects the EN 10270-1 norm – the determination of the free wap diameter W and the axial displacement fa of a ring taken from a wire coil (cf. Figure 12). While the standard intends the measurement to be made from a single ring of wire, it is possible to take numerous random samples from the coil, make the same measurement, and come to conclusions about the wire's uniformity. By way of example, Figure 11 gives the data for the coils of wire which were used for the tensile tests in Figure 10 and the winding tests in Figure 9. The method provides an initial comparison between variations in geometry and variations in strength. There is an obvious association between the tensile strength Rm and the changes in the wap diameter W. To eliminate any influence of the drawing machine on the measurements, both wires were drawn on the same machine using exactly the same set of dies. The lower spring in Figure 9 was made from "wire 2" and the one above from "wire 1".

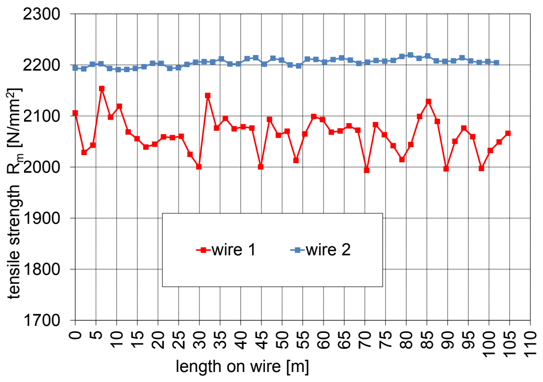


Figure 10: 50 tensile tests on two different types of wire

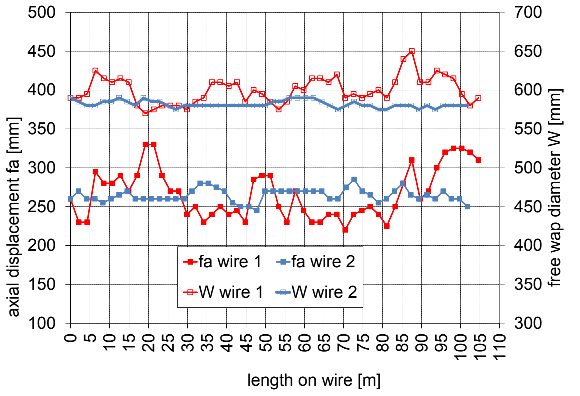
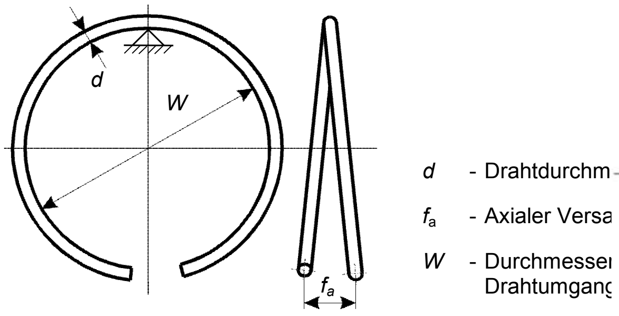


Figure 11: axial displacement *fa* and free wap diameter *W* on two different types of wire



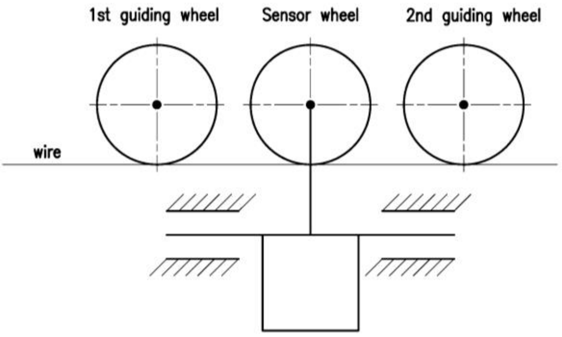


Figure 12: f_a (axial displacement) and W (diameter of a free wap) as indicated in EN 10270-1 (2012)

Figure 13: Schematic representation of the "sensor wheel" measuring setup

Using the "sensor wheel" measuring setup developed by the research group it is possible to find the uniformity of the wire properties along the entire length [4]. For "continuous" wire it is thus possible to monitor the uniformity throughout the whole coil.

In absolutely every wire drawing process, that is in every wire drawing machine, the wire is deformed. However, the deformation is not only the obvious type, i.e. the reduction in cross-section, but the wire is also deformed during the process in the direction of its bending by interaction with the drawing machine – among the reasons for deformation are bending at the guide rollers and fluctuations in the tuner rolls for the individual drawing stages. If one imagines two pieces of wire of different strength which are shaped into an identical curve, the wire with the higher strength will deform with less plasticity. In theory, the same thing happens when wire is being drawn.

The variations in strength due to the rolling of the wire will also result in different radiuses of bending and consequently in varying free wap diameter.

Again, wires 1 and 2 are presented as an example of the phenomenon. Looking first at the signal from the sensor wheel as recorded and then represented in relation to wire length (Figure 14 and Figure 15), far greater variation is clear for wire 1 than the variation for wire 2. The significance is that in the case of wire 1 the sensor wheel has recorded much greater differences between the forces produced by the wire along its axis than in the case of wire 2. So that the statement is even more accurate, the representation is of the frequency distribution for the signals recorded. The method shows clearly how often the sensor wheel recorded the measured values in the particular classes: the narrower the distribution, the more "uniform" is a wire. Wide frequency distribution, on the other hand, means that the values varied very considerably, indicating that the wire is far from uniform. Figure 16 and Figure 17 give a comparison between the frequency distribution of the sensor wheel signals and the distribution of the tensile strength Rm of the relevant wires. This comparison makes it plain than a wire possessing wide variation in tensile strength also possesses much variation in its geometrical properties – and vice versa. The method permits definite prediction of variation in tensile strength for a wire to be made from the (non-)uniformity of shape.

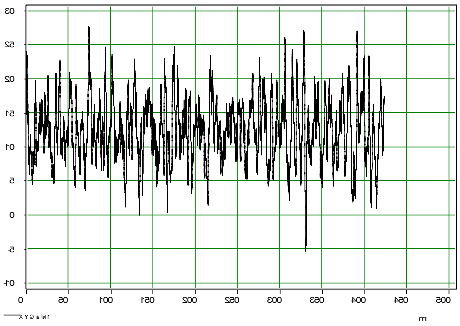


Figure 14: Sensor wheel signal represented across wire length, "wire 1"

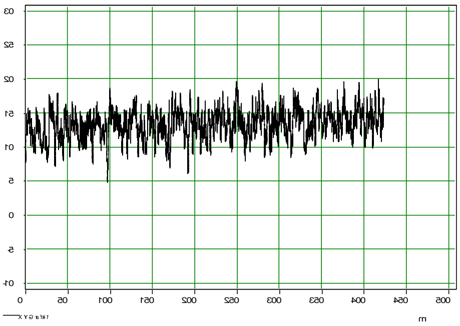


Figure 15: Sensor wheel signal represented across wire length, "wire 2"

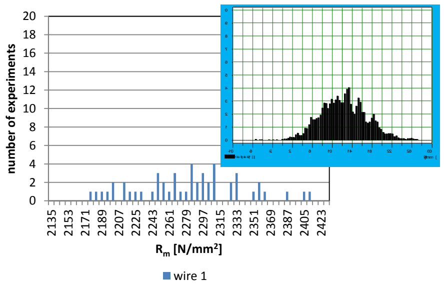


Figure 16: Frequency distribution of sensor wheel signals for "wire 1" and tensile strength R_m [5]

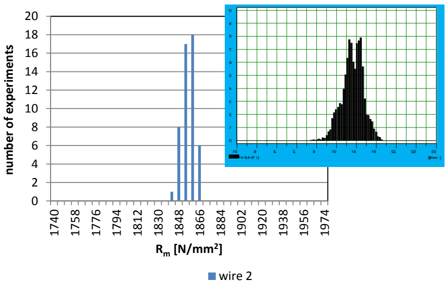


Figure 17: Frequency distribution of sensor wheel signals for "wire 2" and tensile strength R_m [5]

5. PROSPECTS AND USFULNESS TO INDUSTRY

The research on the 48 sample wires shed light on the natural and artificial age-related alterations in mechanical properties in relation to numerous wire manufacturing parameters.

Using the sensor wheel measuring method here presented, 100 % monitoring of wire uniformity (both of tensile strength and of shape) will be ossible during production. The experiments are applicable and potentially useful not only for spring steel wires, but also for welding wires, bead wires, steelcord or rope wires. The sensor setup might also be applied to the monitoring of the drawing parameters during drawing.

The method of crack detection and evaluation which has been developed could be transferred with little further effort to the torsion test benches used in industry.

6. ACKNOWLEDGMENT

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REFERENCES

[1] EN 10218-1 Stahldraht und Stahlerzeugnisse; Allgemeines Teil 1: Prüfverfahren; 1994
[2] Schneider, Fr.: Stahldraht; VEB Deutscher Verlag für Grundstoffindustrie; 1973
[3] Schumann H., Oettel H.: Metallografie. Wiley-VCH, 14. Auflage, 2005
[4] Bretschneider, I.; Wauro, F.; Lutz, S.; Geinitz, V.; Beyer, P.: Neue Ansätze zur Ermittlung der Werkstoffkennwerte von Federdrähten. Tagungsband 44. IWK/1999 der TU Ilmenau 1999
[5] Lux R. et al..: Langzeitstabilität der mechanischen Parameter patentiert-gezogener Stahldrähte. AiF-Projekt 17043BR: Abschlussbericht 2013

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