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measuring roll in strip processing lines**



New development of a high-precision shape measuring roll in strip processing lines

Ch. Moos, BWG GmbH

BWG GmbH in Duisburg is known worldwide as a high-quality, innovative machinery and equipment supplier in the metals industry. BWG's supply range includes, for example, tension levelling lines, heat treatment and coating lines for aluminium automotive sheet, and skin pass mills for aluminium, steel, and stainless steel. The company's portfolio has always included a large number of patented new developments in order to optimize individual process steps. Following this tradition, the product scope has now been supplemented by a further new development, adding the high-precision BWG shape measuring roll, specifically tailored to customer requirements.

An inherent characteristic of many processes during the production of flat-rolled metal parts is the formation of internal stresses of various kinds in the semi-finished product, which can lead to undesired behaviour in downstream processes. Associated with the inherent stresses is the technological concept of shape and flatness. If the magnitude of inherent stresses exceeds a certain limit, waves or bows appear, leading to deviations from a perfect flat shape. This may occur offline in a cut-to-length sheet or inline in sections where the magnitude of strip tension is not high enough to compensate for the inherent stress, leaving locally compressive longitudinal stresses above the critical limit. Problems can arise near the end of the manufacturing chain, e.g. in deep drawing for the production of car body parts for the automotive industry. Or further 'upstream', for example when handling the strip in the entry of a strip processing line or in the process sec-

tion itself, or in slitting lines, etc.

Finally, in certain process steps, the shape is also a suitable measure to judge the quality of the process indirectly, e.g. during the skin pass rolling of aluminium or steel sheet, because the distribution of inherent stresses in the strip after the skin pass mill is linked to the roll force distribution in the transverse direction in the roll gap, which in turn directly affects the uniformity of the surface structure to be transferred from the work rolls to the strip. This makes the measurement and, if necessary, the introduction of countermeasures to avoid unwanted inherent stresses today an indispensable recurring component throughout the entire process chain.

Expert literature has described and defined the recurring shape defects in metal strips in detail [1, 2]. The typical phenomena are subdivided into 'unwindable' and 'non-unwindable' types of defects. Unwindable shape defects are those which can be eliminated by plastic bending without superimposed tension. These include coilset (curvature vector transverse to the longitudinal strip axis) and crossbow (curvature vector in the direction of the longitudinal strip axis). Non-unwindable shape defects are caused by plastic elongation varying across the strip width.

These internal stresses originate from a number of situations, including a mismatch of roll gap geometry with the cross-sectional thickness profile in cold rolling or creep in the wound-up coil, among others. The differing elongations are compensated by inherent stresses (via Hooke's law). Strip tension is superimposed over the inherent stress distribution, but if strip tension is low or absent, the result are local compressive stresses in the sheet. If the compressive stresses exceed a critical value, buckling occurs and waves

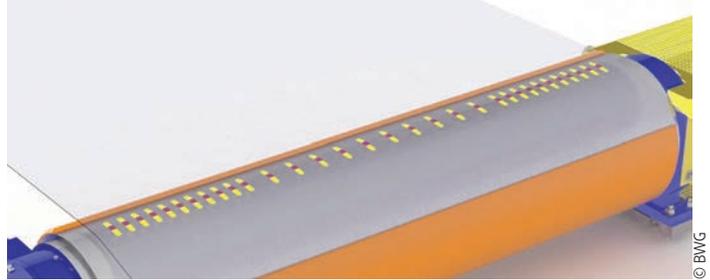


Fig. 1: BWG shape measuring roll

are formed ('manifest shape defects'). If the critical stress is not exceeded, no waves are formed and the defects are not visible optically ('latent shape defects'). This well-known physical behaviour severely restricts the usability of certain types of shape measuring systems: all non-contact measurements based on optical or electromagnetic fields can only detect shape defects if the physical conditions permit strip buckling and formation of waves. Depending on the cross-sectional stiffness of the sheet, considerable inherent stresses may be present without any manifest shape deviations [3], and these systems are unable to recognize them.

A widely used measuring principle that avoids this limitation is the deflection of the strip around a shape measuring roll in which force sensors are incorporated in order to measure the radial contact force between the strip and the roll. As the strip travels over the measuring roll, the non-constant distribution of strip tension resulting from the non-unwindable shape defects leads to a non-constant distribution of the strip to measuring roll contact force, which is to be detected with the force sensors installed in the measuring roll. Fig. 2 shows the measuring principle in schematic form. Unwindable shape defects generally cannot be detected with this principle.

The development of a shape measuring roll that fulfils this task was the self-imposed goal for BWG. The concrete requirements for the system to be developed were as follows:

1. The system should be able to detect local differences in fibre elongation of 10 $\mu\text{m}/\text{m}$, corresponding to one I-Unit (definition see below), even in thin strips (0.25 mm)
2. A reliable measurement of the inherent stress profile should be available after only one turn of the shape measuring roll
3. The detection of the inherent stress profile

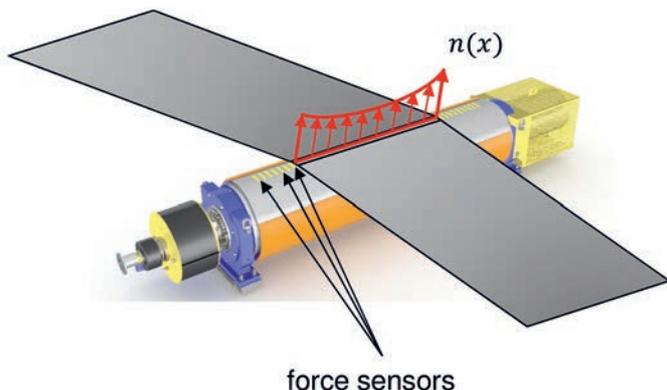


Fig. 2: Schematic representation of the measuring principle

should be independent of time-dependent variations of overall strip tension

4. Strong gradients in the strip tension profile (often found close to the strip edge) must also be detected

5. The design must of course be suitable for industrial use (robust and low in maintenance).

6. The shape measuring roll should be applicable for length-related quality monitoring and logging in strip processing lines. This latter point is connected to the fulfilment of the first five points, of course.

Measuring accuracy: strip shape defects are usually quantified in I-Units [IU]. There are different definitions in use: the first refers to the optical shape errors by correlating wave height and length in the buckled sheet, the so-called ‘flatness index’, [1]:

$$I_E = \left(\frac{\pi f_i}{2\lambda_i} \right)^2 \quad (1)$$

Here, f_i denotes the amplitude and λ_i the wavelength of an assumed sinusoidal waveform. The index i refers to an imagined partitioning of the strip into longitudinal fibres with finite width. The sometimes used waviness W is linked to the flatness index:

$$W = \frac{f_i}{\lambda_i} = \frac{2}{\pi} \sqrt{I_E} \quad (2)$$

Another definition refers directly to the differences in fibre length across the strip width. The length difference Δl_i of a local fibre is set into relation with the reference length of the sheet being examined

$$I_p = \frac{\Delta l_i}{l_{Ref}} \cdot 10^5 = 10^5 \Delta E = \frac{\Delta \sigma}{E} \cdot 10^5 \quad (3)$$

with Young’s Modulus E of the strip material, the maximum strain difference $\Delta E = E_i - E_{av}$ and the maximum stress difference $\Delta \sigma = \sigma_i - \sigma_{av}$ from the average values, respectively. Stresses and strains are connected via Hooke’s law. Equation (3) defines the ‘shape deviation index’ [1]. An alternative definition is given in [3]: a distinction is made between direct and indirect I-Units. The definition of direct I-Units is the same as for the flatness index, equation (1). Indirect I-Units are defined as

$$I_{Indirect} = \frac{\sigma_{max} - \sigma_{min}}{E} \cdot 10^5 \quad (4)$$

It is clear that indirect I-Units (or flatness index) and direct I-Units (or shape deviation index) usually do not yield the same numerical value for a specific sample, especially when the critical buckling stress is not exceeded within the strip, because then internal stress differences are present (non-zero indirect I-

Units/shape deviation index) but no waves appear (zero direct I-Unit/flatness index). See [3] for further analysis of this topic. The thicker and stiffer the material, the higher the difference between both values can be. A shape measuring roll always measures the shape deviation index according to equation (3), and it is therefore obvious that the central ability a shape measuring roll must have is to detect small differences $\Delta \sigma$ between different measuring points. The correlation of both indices has been studied by virtue of the Finite Element Method (FEM) in [3].

Calculations for different situations (thickness, material properties, width-to-length ratios of sheets, types of inherent stress profiles) have been evaluated. Such calculations are far too resource-consuming and slow to be synchronized with a shape measuring roll system. However, for every application scenario an adapted, simpler empirical model can be formulated and calibrated with the FEM-model, thus providing an effective estimate about the flatness index based on the measured indirect I-Units or the shape deviation index, respectively.

The accuracy a given system can reach while measuring the shape deviation index depends on the material, because one I-Unit always refers to the same strain difference (10 $\mu\text{m}/\text{m}$) and thus to different stress differences for materials with differing Young’s Moduli. The stress profile is measured indirectly via the contact force between strip and roll. In a first approximation, the measured force acting on a sensor depends on the tensile force in the part of the strip lying above the sensor:

$$F_{meas} = 2 \sin\left(\frac{\alpha}{2}\right) \cdot \sigma \cdot b_{sensor} \cdot h \quad (5)$$

Where α is the wrap angle around the shape measuring roll, b_{sensor} is the design-related width of the measuring zone, h is the strip thickness and σ is the strip tension averaged over the measuring zone. This approximation is only partially true, and is generally not sufficient for shape measuring rolls, as will be explained below. But it is accurate enough to analyze the dependence of the measurement accuracy on different parameters. As can be seen in equation (5), the required resolution of the measuring force depends not only on the minimum magnitude of $\Delta \sigma$ still to be measured precisely, but also on three further parameters, two of which (wrap angle α , gauge width b_{sensor}) are determined by mechanical design of the system and the third (the strip thickness h) from the product range of the system.

Piezoelectric force sensors are used which,

for a shape measuring roll, have several advantageous properties in comparison to conventional resistive strain gauges: they allow the measurement of large forces while exhibiting only very small displacements, and they provide a constant measurement accuracy over a wide measuring range. The second point means that the absolute value of the force measured plays less of a role in determining resolution and accuracy. Thus the thinnest strip in the product mix becomes critical for assessment of the achievable accuracy, because for a given σ the resulting force on the sensor becomes smallest for the smallest h , and likewise does the force differences corresponding to a given stress difference $\Delta \sigma$.

The parameter b_{sensor} influences the quality of the measurement in two opposing ways: the larger it gets, the greater the resulting force per 1 MPa of strip tension acting on the sensor, but the larger the area over which the local strip tension is averaged. The actually existing strip tension profile is blurred by wide measuring zones to a greater extent, which is undesirable, especially in the region of the strip edges. The minimum width of the measuring zones, on the other hand, depends on the size of the selected sensors.

With an increase in the wrap angle α , the measured force difference per 1 I-Unit is also increased, but this cannot be continued arbitrarily, as Fig. 3 shows: if the wrap angle is so large that the entire measuring point is covered in the strip running direction, then only a fraction of the complete contact force belonging to the measuring zone acts on the sensor.

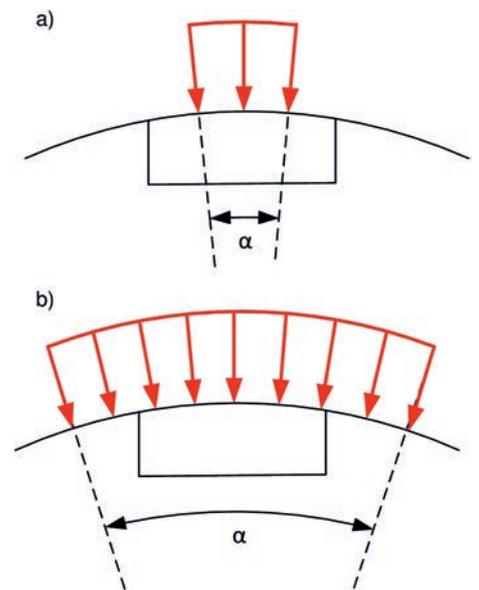


Fig. 3: Contact force between strip and roller at different wrap angles α
a) Contact zone shorter than measuring zone
b) Contact zone longer than measuring zone

In a first approximation (according to Euler-Eytelwein theory) the local contact force per surface area does not change with an increasing wrap angle, and thus the resulting force on the sensor cannot be further enlarged.

In addition to these parameters, there are other minor aspects to consider when designing the single measuring point. The intensive investigation of the interplay of these parameters and the expected signal form has led to a novel design of the measuring points for the BWG shape measuring roll (see Fig. 4).

Two piezo elements are installed per measuring zone, and sealed with a feather-key shaped cover (see Fig. 6a). The mounting force required for piezoelectric force transducers is applied with screws from inside the roll in order to avoid unwanted disturbance of the roll surface. The longitudinal axis of each measuring zone is aligned to the strip running direction. The wrap angle is chosen in a way that at no time the complete sensor cover is in contact with the strip but only a portion of it. This results in a rectangular contact zone (see blue area in Fig. 6a). The

resultant contact force on the sensor cover is distributed on both sensors (sensor forces F_{S1} and F_{S2}),

$$F_{\text{resultant}} = F_{S1} + F_{S2}$$

as long as the contact zone is on the rectangle part of the sensor cover, between both sensors. The forces F_{S1} and F_{S2} change while the contact zone moves across the sensor cover, but the sum of both remains constant. Both signals are summed up electrically, thereby producing a signal with an almost constant plateau for the time of the run-over, as depicted in Fig. 4b. This form allows the calculation of the mean value over a finite time period, eliminating the influence of noise and other minor disturbances almost completely. This reduces the uncertainty of measurement considerably compared to a circle-shaped sensor cover that produces a signal with a singular peak (see Fig. 4c). An increase of the wrap angle has two opposing effects on accuracy. A larger angle induces larger contact forces for the same strip tension according to equation (5) which are easier to measure, while at the same time the length over which averaging is possible is reduced. Because the time when the complete contact zone is between the two sensors is shortened, this has the opposite effect on the accuracy. The optimal wrap angle for the BWG shape measuring roll is determined using a mathematical optimization algorithm.

In terms of design, this design offers even more advantages: The measuring zone can be made significantly narrower compared to the case of circular holes where the cable connector determines the diameter of the sensor cover. The measuring zone width of the BWG shape measuring roll is approximately 18 to 28 mm depending on the application. When metal strip is bent around a deflector roll with a small wrap angle, the actual wrap angle does not necessarily coincide with the theoretical one. Depending on the strip thickness and strip tension, a smaller angle is established, up to the point where the strip does not follow the roll radius at all and the contact zone is practically a straight line. This behaviour creates the difficulty that depending on the actual wrapping at a circular measuring point, no rectangular contact zone is formed (see Fig. 4.) Thus, with circular sensor covers the complete strip force is not detected, and a precise knowledge of the contact zone or the actual wrap angle, respectively, would be necessary for correct interpretation of the sensor signal.

The key-shaped sensor cover in the BWG shape measuring roll prevents this problem

from the outset, as there is always a rectangular section of the contact zone above the measuring zone. Due to the high stability of the measurement, a reliable strip tension profile is available right from the first contact between the measuring points and the strip. No averaging over several roll turns is necessary. The selection of sensors and the interaction of the mentioned parameters must be adapted to different applications. Especially for thin strips (≤ 0.5 mm), a wider sensor cover must be chosen than for strips above 1 mm, in order to 'capture' enough resultant contact force for a precise measurement. As explained, the resolution achieved in I-units depends on strip thickness, strip material properties and installation. Some values typically achieved with the BWG shape measuring roll are presented here:

Material	Strip thickness	Resolution
Steel	0.25 mm	0.5 ± 0.3 IU
Aluminium	0.25 mm	1 ± 0.4 IU

Independence from fluctuations in strip tension: the sensors of the BWG shape measuring roll are arranged in a row, so that the strip tension profile is recorded simultaneously for the entire cross section. This prevents the measured profile from bias resulting in fluctuations of strip tension during the measurement.

Detection of gradients in the strip tension profile: close to strip edges one typically encounters high gradients in the strip profile, for example those originating from thermal camber during cold rolling. A discrete sampling of the profile inevitably leads to a homogenization of the measurement in comparison to the actual situation. There are three

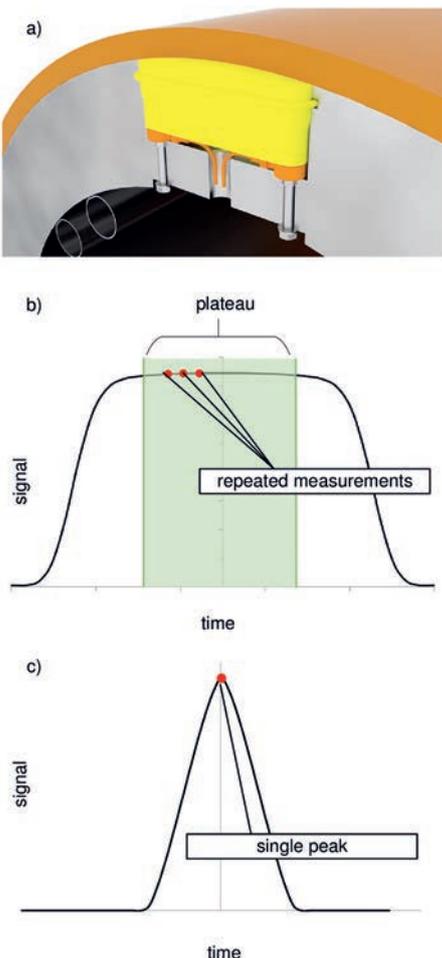


Fig. 4: Patented design of the BWG shape measuring roll a) 3D view of the measuring point b) Time dependent signal while measuring point is in contact with strip c) For comparison: time dependent signal for circular sensor cover

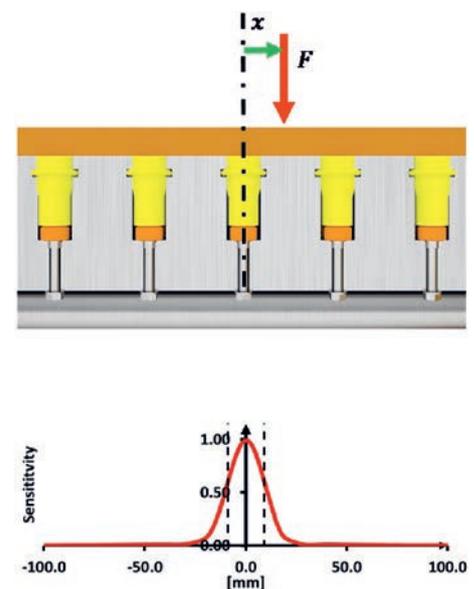


Figure 5: Scattering behaviour of PU coating

different configurational parameters for a shape measuring roll to be accounted for if the aim is to analyze the ability to capture high gradients. These are: the distance of the measuring zones from each other, the width b_{sensor} of the measuring zones, and the supporting or scattering behaviour of the roll body and coating (so-called force-spread behaviour). The distance and width of the measuring zones are of course dependent on each other. It has already been explained that narrow measuring zones are possible due to the advantageous design of the BWG measuring points. The distance of the measuring zones can be chosen to be 50 mm or less. Distributed in three rows around the circumference, a complete coverage of the entire strip width can be achieved. Since the rows are not evaluated at the same time, the number of channels and thus the costs for the transmitter are not increased.

This leaves the influence of a coating to be discussed: The BWG shape measuring roll can be supplied with various coatings, for example tungsten carbide or polyurethane (PU). The contact force between roller and strip is scattered by the coating. Fig. 5 shows the scattering behaviour as an example for a 15 mm thick PU coating and an 18 mm wide measuring zone. If a concentrated load acts on the surface of the roll, located at a distance d in axial direction of the measuring zone, a certain signal is produced by the sen-

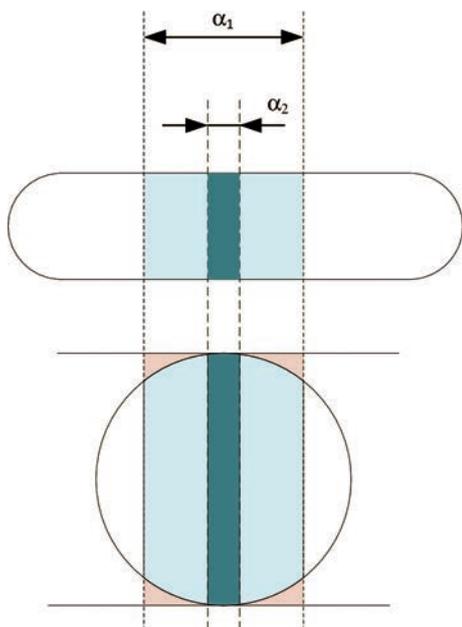


Fig. 6: Contact zone between measuring point and strip at different angles of wrap α_1 and α_2 . In the case of the feather-key shaped cover, according to the BWG principle, the contact zone is always a rectangle. With the circular cover, only a portion of the strip force acts on the sensors (missing the red areas)

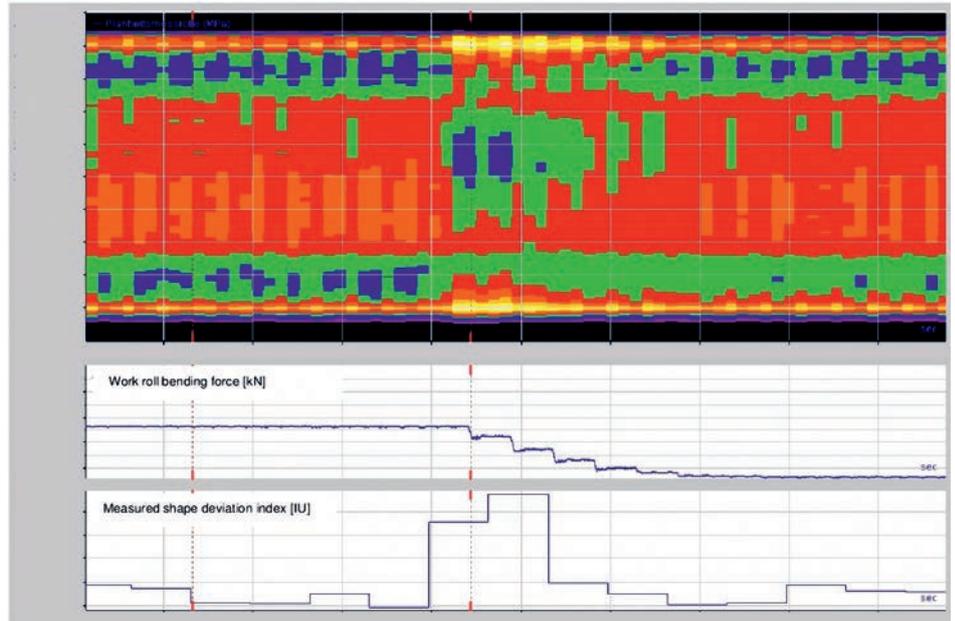


Fig. 7: Recording the responses in the flatness image after a skin pass mill to changes in the actuators during commissioning. Here: first, the rolling force is changed so that the flatness is deliberately deteriorated. The plan position control adjusts the work roll bending.

sors. Obviously, with increasing distance d the signal gets ever lower, but even if the force acts outside of the measuring zone there is some signal left. The relative magnitude of the signal with respect to d is depicted in the graph in Figure 5 below.

Accordingly, in case of a contact force distribution on the roll surface, areas outside the measuring zone contribute to some extent to the resultant force on the sensors. If the distribution is constant, i.e. originating from an ideally flat strip, the crosstalk of neighbouring zones is mutually evened out. But a non-constant profile is, in addition to the blurring by finite width measuring zones, further homogenized by the force spread when there are high gradients present. A certain level of force spread is unavoidable, but it is important to keep the effect as small as possible. It is controlled by the thickness of the coating and the stiffness of the material. Here, too, opposing design effects arise: as the measuring zone narrows, an ever narrower part of the strip is scanned, contributing to finer parallel resolution. But in addition to the reduction of the measuring force difference per 1 I-Unit, this also means that the relative proportion of the scattered force is increased. The phenomenon of scattering has been analyzed by BWG with continuum-mechanical methods and has been experimentally substantiated on purpose-built test facilities. This deep understanding enables a smart choice for the combination of coating and measuring zone width. Besides that, it allows the processing of the signal from only partially covered measuring

circumstances even the evaluation of measuring points just outside the strip. A prerequisite for the latter two points is a precise knowledge of strip position (provided by an additional position measurement). Finally, the question of a correct calibration of a shape measuring roll can only be answered with a deep understanding of this behaviour.

The electrical currents coming from the active piezoelectric force transducers are converted into force proportional voltages in special charge amplifiers. These are in turn picked up by downstream electronics, digitized and subjected to some pre-processing. With modern industry-standard Wlan technology, the data is transferred to a process PC in the switchboard, where it is further processed and prepared for visualization and use in a closed-loop control.

The BWG shape measuring roll is suitable for various application scenarios:

Shape control on skin pass mills: the flatness measuring roll is placed just after the

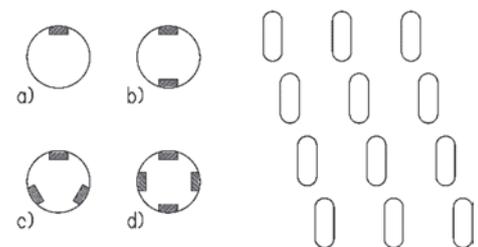


Fig. 8: Different roll configurations: a) Base with one measurement series, b) Two measurement ranges (180°), c) Three measurement series (120°), d) Four measurement series (90°). Right: Representation of the measuring point arrangement in four-row configuration (image is not to scale)

roll gap (about 2 m distance). The measured strip tension profile is matched with a stored nominal curve and the actuators influencing the flatness are adjusted in a way that the deviations from the target curve are minimized. The closed-loop control can be linked to a process model to make it more predictive. The suitable configuration depends on the influencing possibilities of the strip tension profile by the actuators of the skin pass mill. One or two-row configurations are available (a) and (b) in Fig. 8), with the second row being offset from the first to achieve higher parallel resolution across the strip width. In order to eliminate bias induced by strip tension variation, a reference measuring gauge is placed in the centre of each row. These reference gauges have no offset to each other and thus allow by direct comparison the level of variation in strip tension, and a corresponding correction when the measurements of several rows are put together to form one strip tension profile. This technique is patented by BWG.

Closed-loop control of BWG Levelflex®: the shape measuring roll is placed within or after the outlet bridle of the Levelflex®, typically in conjunction with a crossbow measurement. Again, a closed-loop control in conjunction with a process model can be provided to control the actuators (amount of strip stretch, inflatable roll diameter, and position of leveling rolls). Furthermore, the shape measuring roll is a valuable aid during equipment commissioning and ongoing process optimization. Here, too, the options a) and b) in Fig. 8 are useful if the shape measuring roll is not to be used for quality monitoring at the same time.

Assessment of final shape (quality control) in strip processing lines: due to its high precision and the fact that a reliable result for the strip tension profile is already available after the first roll turn (which means that variations in the shape may also be located precisely), the BWG shape measuring roll is excellently suited for logging the final shape in strip processing lines and for providing quality records. Customer confidence in the products

can be increased, thus achieving a competitive advantage over other metal producers. For this application, three or four-row variants are available (c) and (d) in Fig. 8). The rows are arranged with off-set to each other so that a parallel resolution of 12.5 mm can be achieved.

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Author

Dr. Christoph Moos is R&D engineer at BWG Bergwerk- und Walzwerk-Maschinenbau GmbH in Duisburg, Germany.