Flatness measurement in cold rolling mills and strip processing lines is most commonly carried out with measuring rolls designed to operate simultaneously as deflector rolls. The known BFI-shape measuring roll, with more than 800 worldwide installed and successful operating applications, is also based on this principle. According to the latest design force sensors are mounted in axially parallel bores, which are executed as through-holes close to the shell surface of a solid roll body. This arrangement provides a robust design with a completely gap-free roll surface over the entire cylinder width. The new roll type opens up new variation possibilities of the roll surface design as well as new applications of this measuring system. The high load capacity of the piezoelectric force sensors and the non-contacting optical signal transmission contribute to a fail-safe and nearly maintenance-free system.

**STATE OF THE ART**

Out-of-flatness may occur on strip and sheet metal both during the production of these products in hot and cold rolling mills and during downstream treatment processes. This is caused by localized differences in the degree of plastic deformation across the strip width or thickness, which in turn lead to differences in the level of internal stresses in the strip material. Deviations from ideal strip flatness occur when the internal stresses in the strip exceed a certain critical value, called the critical buckling stress.

In cold rolling mills, strip is produced and coiled under tension, which partially can assume high values. Length deviations being present in the strip are stretched out by the applied tension in such a way that the strip appears to be flat during rolling. However, latent flatness deviations are present in the strip and appear later when the strip is uncoiled. This can result in production stoppages, reduced output and poorer quality. In order to be able to influence flatness deviations during the rolling process itself, using the adjustment systems on rolling stands, flatness measuring systems are required. These measuring systems have to be capable of being used in diverse types of rolling mills and strip treatment lines and must deliver precise results, irrespective of the steel grade and its dimensions. Since the strip is subjected to longitudinal tension in most strip treatment lines, the tensile stress distribution, which itself is dependent on the length distribution, is used to determine deviations in strip flatness. Various methods are used to determine the tensile stress distribution.

Some measuring methods apply external forces to the strip, causing it to be displaced, in order to determine the differences in strip tension. These forces can be generated by magnetic fields or by oscillating negative-gauge pressure (vacuum principle), for example. The measurement of the local displacement is then used to determine the equivalent strip tension distribution across the strip width.

Displacement measuring systems are normally installed between the roll gap of the rolling mill and the deflector roll before the coiler (Fig. 1a). However, since the strip is unsupported and moves freely through this space, strip displacements may occur that are not attributable to longitudinal tensile stresses and will therefore cause spurious measurements.
In thin strips, the longitudinal tensile stress applied to the strip may therefore result in elastic necking and folding (Fig. 1b). These folds generate a bending resistance similar to that of corrugated plate-sheet, which will restrict the extent of strip displacement under the applied displacement forces and will cause errors in flatness measurement.

In thick strips, bending of the strip around the deflector roll will cause a length bow which in turn results in a cross bow due to cross contractions. If this cross bow has superimposed flatness deviations, such as long strip edges, the direction of the cross bow will change from upwards to downwards in an uncontrolled manner during displacement of the strip. The flatness measuring system then wrongly registers this change of direction as a flatness deviation (Fig. 1a).
Length bows and the resulting cross bows can be caused by other factors besides bending of the strip around the deflector roll. They may also occur due to asymmetries in the roll gap, which will aggravate the formation of the cross-bow due to the bending process.

There is another bow-effected influence on the result of flatness measurements obtained with displacement measuring systems. As the length bow becomes more pronounced, so does the distance of the strip from the measuring system, so that the strip may move out of the range of the measuring system (Fig. 2b). Experience has shown that, unless additional strip guidance rolls are installed, displacement measurement systems are suitable only for strip thicknesses in the range of 0.2mm and 2mm.

Displacement methods using the vacuum principle have an additional drawback. The positive atmospheric pressure prevailing at the strip edges results in an undefined pressure condition in this zone, so that no precise measurement is possible. Measurements in this zone are, however, especially important for flatness control.

The methods most commonly used to measure strip flatness deviations measure the radial force exerted by the longitudinally tensioned strip as it is deflected around the deflector roll. This radial force varies locally as a function of differences in tensile strength distribution across the strip width. By using suitable measuring rolls with measuring zones distributed across the width of the roll cylinder it is possible to determine the local radial force and to calculate the tensile stress and hence the length distribution across the strip width (Fig. 3a).

Because there is direct contact between the strip and the measuring roll, these measuring systems are free of the error sources inherent in the above-described displacement measuring systems.

The well-known BFI Flatness Measuring Roll, of which more than 800 are now in use around the world in a wide variety of cold-rolling mills and strip treatment facilities, also operates on this deflection roll principle. BFI’s strategy is to replace the deflector rolls which are in any case required before the coiler with measuring rolls designed to operate simultaneously as deflector rolls. This avoids the installation of separate measuring systems that would take up additional space (Fig. 3b).
The flatness measuring roll as the core of the BFI flatness measuring system has been systematically improved over the past few years. The main focus of this development effort has been to improve the measuring roll construction and to broaden the range of possible applications in strip production. The particular characteristics of the latest roll generation are detailed below.

**BFI FLATNESS MEASURING ROLL (A-TYPE)**

**Mechanical structure**
The roll body is made of roll steel and consists of a solid roll body exhibiting an uninterrupted, smooth, gap-free and homogeneous roll surface over its entire cylinder width (Fig. 4).

![Fig. 4: BFI flatness measuring roll (A-type)](image)

Depending on customer preference, the surface of the roll body may be hardened or plated with a wear-resistant material such as hard chromium or tungsten carbide. Elastomer (special rubber) or polyurethane coatings can be applied to the roll body without extensive surface preparation. Similarly, the roll surface can be provided with different roughnesses or textures to produce defined roll-to-strip friction conditions where this is desirable for process reasons. Especially for use in higher strip temperature ranges as encountered in the production of silicon steel strip, for instance, the roll body can also be supplied in a high-temperature version for temperatures up to 300°C.

According to the measuring operation requirements, the roll body can be manufactured to different diameter and cylinder width specifications. The measuring rolls produced to date vary between 160 and 700 mm in diameter and between 550 and 2400 mm in width. The roll necks may be either integral with the roll body or attached to it as separate components via flanges. To accommodate the force sensors, axially parallel bores are provided in the end faces of the roll body (Fig. 5).
Fig. 5: Measuring roll body with axial bores

Arranged at a distance of 5 to 11 mm from the shell surface, these bores may be through-holes extending over the full cylinder width or be produced as blind holes. The diameter of the sensor mounting bores can be between 30 mm and 50 mm, depending on the force sensor type employed. Between 2 and 6 such axial bores can be provided, depending on the desired number of force sensors and the wrap angle of the strip around the roll body when in service. Special tapered sleeves have been developed to receive force sensors which are introduced into the bores from the roll end face and positioned at different depths. By means of the tapered sleeves the force sensors are fixed in place with a high level of prestress.

Depending on the bore depth, up to 24 force sensors can be fitted in a single bore in this manner. By offsetting the sensors over the width of the measuring roll cylinder, the sensors can be axially positioned so that there will be one sensor every 10 mm from one bore to the next. This is particularly beneficial for precise measurements in the strip edge area or where tensile stresses vary widely within narrow strip zones.

Fig. 6: Axial bore with mounted force sensor
Electronic structure
As with previous BFI Flatness Measuring Rolls, the new generation rolls use proven piezo-electric force sensor technology (Fig. 7). These force sensors are very small yet can handle high loads at extremely low levels of elastic deflection. The action of mechanical pressure loads on the piezo quartz sensor produces a charge which is converted into a force-proportional voltage by the so-called charge amplifier. The piezoelectric sensors are passive force sensors requiring no electrical power supply.

Fig. 7: Piezo force sensor (Kistler standard type 9051A)

Outstanding features of these piezo quartz force sensors include:

- extremely broad measuring range: 0.01 N to 120,000 N
- broad temperature range: -196°C to 200°C or 300°C
- high linearity: < 0.3 %
- high load capacity: 144 kN
- high stiffness up to: 9 kN/micron
- very low hysteresis: < 0.5 %

Since the force sensors in different bores are distributed at different angular positions over the circumference of the measuring roll, the staggered sensors are not exposed to strip loads simultaneously. So they can be connected in parallel to provide input to a common charge amplifier (Fig. 8).
In conjunction with this charge amplifier with "on-line" switchable gain, these force sensors can deliver readings of a constantly good resolution across different force ranges. On a high reversing cold rolling mill for stainless steel strip, for instance, the system can measure forces over a 1:200 range without any change in resolution quality.

This high measured-value resolution is achieved by:

- Adapting the charge voltage converters to the rolling mill and production parameters
- Online switching of the charge voltage converters between 3 amplification ranges during rolling mill operation
- High resolution of over 1/4000 (72 dB) per amplification range

For reliable transmission of force measuring signals from the flatness measuring roll to the measurement processing unit, the signals are digitised and encoded by pulse code modulation. The transfer of signals from the rotating measuring roll to the stator unit is achieved in a non-contact manner by means of infrared light. The charge amplifiers, encoders and transmission modules are integrated into one compact unit in a housing flanged to the measuring roll. (Fig 9).
This housing also contains a 5000 ppr incremental encoder which allows precise correlation of the sensor positions with the force signals. It can also be used as a measuring transmitter for mass flow control, for example.

Following the transmission of the digitised signals from the rotating measuring roll via the stator to the electronic interface unit placed in the switchgear room, the signals are decoded and fed to the processing algorithms. The measuring signals, operating and equipment parameters are linked via these processing algorithms in the DSP processor so that the flatness data obtained can be output as required for control and display purposes.

The data communication to display and control the flatness at the rolling mill is based on the TCP/IP protocol.

**Special features**

In existing measuring systems, the measuring zone distribution and the number of measuring points are fixed. With the new BFI measuring roll (type A), on the other hand, the special sensor installation technology means that the number of sensors and their positioning can be adjusted after delivery without any modification to the roll body. System adjustments of this kind can be made directly on-site in the user’s facilities. This is especially useful in cases when a change in production calls for a different zone distribution or when a sensor has to be replaced.

Since the measuring roll with its smooth, gap-free and entirely homogeneous surface is outwardly completely identical to a normal deflection roll, its behaviour during the production process and its handling during maintenance operations, such as regrinding, is similar to that of any standard deflection roll normally used in its place.

**Operating experience gathered to date**

More than 60 units of the new measuring roll type with axial bores and gap-free surfaces are now either in industrial operation or in production. The measuring rolls are distributed by the German BFI-licensees Achenbach Buschhütten GmbH, SMS DEMAG AG, Siemens AG., Sundwig GmbH, Friedrich Vollmer Feinmessgerätebau GmbH as well as Hess Engineering, USA und Kobe Steel, Ltd., Japan.
These rolls vary between 160 and 700 mm in diameter and between 450 and 2400 mm cylinder width. The surfaces of the rolls currently in service are:

- hardened to HRC 58 •\(^{3/2}\)
- hardened and textured
- hard chromium plated to HV 950
- tungsten carbide plated
- rubberised

The main applications to date include skin pass mills, reversing mills, carbon steel tandem mills, cluster mills for high-grade steel strip, rolling stands for electrical sheets as well as aluminium and copper rolling mills. Over the whole production range of cold rolled products the operating measuring rolls have satisfied the highest demands on strip surface quality.

The operating experience accumulated so far confirms the expected functionality of the system and the high repeatability of the measuring signals. The sensor measuring accuracy is less than 1 l-Unit and the roll measuring accuracy is down to 2 l-Units.

Contact:

Frank Gorgels
Betriebsforschungsinstitut (BFI)
VDEh-Institut für Angewandte Forschung GmbH
Sohnstrasse 65
40237 Düsseldorf
E-mail: Frank.Gorgels@bfi.de