Developments and Benefits from Optical Flatness Measurement in Strip Processing Lines
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1. INTRODUCTION

The interest for flatness measurement, quality assurance and process control has become more important since steel strips have higher quality demands today. In addition, harder and stronger steel is more difficult to produce flat and here an accurate and systematic measurement can help to improve the manufacturing process.

Since a process line is more or less under tension in most cases, the measurement principle is of essence. Shape meter rolls require tension whereas optical methods measure the manifest part of the flatness and works with no or limited tension. Both principles have their pros and cons.

This paper will present both techniques and compare how they stand against each other. The paper will also describe the latest developments of optical flatness measurement done by Shapeline and exemplify usage and benefits of in-line flatness measurement in processing lines.

2. BACKGROUND

Flatness measurement using shape-rolls has been used in cold rolling mills for a long time. The benefit is obvious since the measured flatness profile can be used directly to control roll bending, tilt and cooling profile. It was therefore integrated in the mill control system at an early stage to control the strip shape against a target I-unit profile.

However, since the flatness is also affected by coiling and in down-stream processing lines, there is a need for measurement in a number of places in a steel mill. A shape roll requires high tension and is a large capital investment and there is therefore a need for alternatives. Whereas shape rolls are more or less standard in a cold rolling mill, very few are installed in processing lines today. Instead, optical gauges which measure manifest flatness (flatness not hidden by tension) can be attractive alternatives. It is, however, important to understand under which conditions an optical gauge will give a reliable measurement result and how the measured data can be used to improve productivity, yield and strip quality.

This paper will first describe flatness, definitions, causes for bad flatness and influence of strip tension and temperature (section 4). Then in section 5, different techniques for flatness measurement will be described together with their pros and cons.

Recent technology improvements have enabled new, more economical flatness sensor solutions and one such solution based on a smart camera will be described in section 6. This type of sensor opens up new possibilities, since the sensor is affordable enough to be installed in more positions in the lines and several such possibilities will be described in section 7.

3. WHAT IS FLATNESS

Flatness can be defined in many ways. It is therefore important to clarify what we mean with flatness for steel and metal strips and sheets.

In general, flatness can be separated into four types; Cross-profile, length profile, I-units and local flatness defects. Cross-profile and I-units are systematic, meaning that they can be described in simple ways that are valid for a certain part (length) of the strip, whereas local defects are not. For the understanding of the rest of this paper, here we will describe each type.

3.1. Cross-profile

Cross-profile is a very common flatness defect. It is a curvature in the transversal direction that persists over a certain strip length (see Figure 1). It is often a result of an area difference between the top and bottom surfaces. If these areas are not equal a crossbow is often the result.

The cross-profile can be described as a polynomial of degree 2 or higher. A second degree cross-profile is often referred to as crossbow. A crossbow value is the maximum gap between a straight line running between the strip edges and the strip surface. A crossbow can be positive (dish) or negative (ridge).
3.2. Length-profile

The strip also has a profile in the length direction called length-profile. A length-profile may also be described with a polynomial where a second degree polynomial is often referred to as length-bow or coil-set. A length-profile is normally not visible in processing lines due to strip tension.

3.3. I-unit profile

If a strip has different lengths in different width positions, it will become wavy in a tension-free state. Typically, if the center is longer than the edges it will have center buckles (see Figure 3). To describe this in a systematic way, ABB invented the I-unit in the 70:s when the Stressometer was developed. They defined an I-unit to be a length difference of $1 \times 10^5$ or 10 microns in one meter.

The I-unit has been described extensively in the literature (e.g. [1]) and is only mentioned in this paper for a general understanding.
3.4. Local defects

A local defect is anything that is not systematic. It can, for instance, be one of the following:

- An edge damage
- An isolated buckle
- A lifted corner, head or tail on a sheet.

Figure 4 exemplifies these defects. If the local defect area is small (typically in the mm range) it is normally referred to as a surface defect.

Local defects may occur due to roll damages, damages due to shearing or material handling or quenching.

4. Effects of tension and temperature

Tension and temperature differences affect the flatness in different ways. It is therefore important to take these factors into account.

4.1. Tension

A strip is very seldom tension free. Tension is required to coil, guide and level strips and due to tension some flatness is always hidden (or latent) as illustrated in Figure 5. An optical measurement system measures manifest flatness whereas a shape roll measures latent flatness. Total flatness (as observed when the strip is tension free) is the sum of latent and manifest flatness.
To calculate how much flatness that is hidden, Young’s modulus must be known. Young’s modulus is defined as

\[
E = \frac{F/A_0}{\Delta L/L_0}
\]

Where

\( E \) = Youngs modulus

\( F \) = the force applied

\( A_0 \) is the cross-sectional area

\( \Delta L \) is the elongation

\( L_0 \) is the original strip length

Now since an I-unit is the same as \( \Delta L/L_0 \) * 10^5 the above formula can be written

\[
I = \frac{F/A_0}{E \times 10^{-5}} = 10^5 \times \frac{P}{E}
\]

Where \( P \) is the specific tension in Pascals. If this formula is used to calculate strip elongation per MPa tension for steel, aluminium and copper, the results are according to the following table:

<table>
<thead>
<tr>
<th>Metal</th>
<th>Youngs modulus</th>
<th>Latent I-units per MPa specific tension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>200 GPa</td>
<td>0.5</td>
</tr>
<tr>
<td>Aluminium</td>
<td>69 GPa</td>
<td>1.44</td>
</tr>
<tr>
<td>Copper</td>
<td>117 GPa</td>
<td>0.85</td>
</tr>
</tbody>
</table>

Table 1. The table shows the transformation of manifest flatness into latent when put under tension.

This can be used as a “rule of thumb” to compute the maximum tension permitted to see a certain I-unit value. As an example, a normal specific tension used in strip lines for strip guiding is 15 MPa. Then 7.5 I-units will be hidden in the tension.

Note that the flatness actually hidden also depends on the I-unit profile itself, why these numbers are only an indication.
A frequent question is if it is possible to calculate the real I-unit profile from measurement under tension if the tension is known. The answer is that this is not possible in the general case. To illustrate for this, see Figure 6.

![Figure 6](image.png)

*Figure 6* The left graph shows I-unit profile without tension. There is only manifest tension. The right graph shows the manifest portion of the flatness when the strip is under tension. The latent part is not visible. Note that the I-units that indicate center-buckles in the left graph have transformed completely into latent flatness.

However, if we assume that the I-unit profile is a second order polynomial, it is possible to reconstruct the original. This will not be true in the general case, but may be used where strip shape is relatively consistent.

![Figure 7](image.png)

*Figure 7* Model-based reconstruction of the I-unit profile. The latent part in the right graph (dotted line) can be reconstructed.

4.2. Temperature

During many steel processing operations, the strip temperature changes, e.g. hot and cold rolling, annealing, quenching and tempering. The absolute temperature does not change the flatness, but relative temperatures do. If the center of the strip is warmer than the edges, the difference in thermal expansion will result in center-buckles, which can be measured in I-units. Here we do not take the volumetric thermal coefficient and effects into account, which is a good approximation as long as the strips are relatively thin. Other rules apply in plate mills and roughing mills.

![Figure 8](image.png)

*Figure 8* An uneven temperature over the strip width modifies the I-unit profile.
Since the thermal expansion is different for different materials, this effect varies with material type. See the table below for a relation between temperature difference and I-unit.

<table>
<thead>
<tr>
<th>Metal</th>
<th>Thermal expansion coefficient (10(^{-6})/°K)</th>
<th>Resulting I-unit difference per °K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon steel</td>
<td>10.8</td>
<td>1.1</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>10.1 to 17.3</td>
<td>1.0 to 1.7</td>
</tr>
<tr>
<td>Aluminium</td>
<td>23.1</td>
<td>2.3</td>
</tr>
<tr>
<td>Copper</td>
<td>17</td>
<td>1.7</td>
</tr>
</tbody>
</table>

*Table 2. Relation between the thermal expansion coefficient and I-units.*

Since the temperature profile and I-unit profile are so closely related, it is relatively straightforward to retrieve a “isothermal” I-unit profile if the temperature profile is known.

5. Flatness measurement techniques

In this section, different types of flatness measurement techniques will be described briefly. A more thorough description can be found in [1].

5.1. Latent flatness measurement

The most common method to measure flatness under high tension is the use of a shape meter roll. A Shape meter roll is under constant contact with the strip and measures the pressure profile over the strip width. There are several types of such rolls, e.g.

- The Stressometer (based on Pressductor technology) used by ABB (previously ASEA) since 1967 [2].
- The BFI-roll (based on Piezoelectric load sensors) developed and patented by BFI (VDEh BetriebsForschungsInstitut) in Germany [3]. There are several companies supplying this roll on a license basis.
- Air-bearing shape meters (Pri-metals [4], IHI Engineering [5])

There are many drawbacks with contact based shape meter rolls, such as maintenance costs, calibration, accuracy depends on roll condition etc. Siemens VAI has therefore gone another way and provided a contact-free system that still measures latent flatness [6]. The strip is periodically excited using a vacuum system and then the amplitude is measured using contact-free Eddy-current sensors.

5.2. Manifest flatness measurement

Optical flatness measurement systems are usually based on the triangulation technology. There are, for instance, the following techniques:

- Laser point triangulation
- Laser line triangulation
- White light projection systems

A laser point system has too low resolution in the width direction to fulfil normal industry standards such as EN and ASTM norms [10]. It will therefore not be considered in this paper. The same is valid for other point based systems, such as inductive, ultrasound and capacitive sensors.

A white light sensor is more sensitive to surface reflectivity variations and ambient light. Some of them also require a substantial amount of maintenance since the light-bulb need to be replaced several times per year. In addition, calibration can also be cumbersome. The differences between white light gauges and laser line gauges are discussed in [10].
5.3. Laser line triangulation

Laser line triangulation is based on a (usually) red diode laser with a line producing optics. The line producing optics spread the laser light in one dimension to make a fan of light (Figure 9). It is advantageous to use refractive optics that make the intensity even over material width.

If the surface has a flatness deviation, it may be observed as a slight bending of the laser line. This bending can be observed by a matrix camera and the software can detect the line for every column in the picture. The usual way is to detect the center of gravity of the line in every point with sub-pixel accuracy. Since the intensity itself is not important, only the position of the line, this method is more robust than competing techniques. By synchronizing the measurement with the line speed, an even measurement point distribution over the surface can be obtained and detected flatness defects matches with the physical position on the strip.

![Camera image](image.png)

**Figure 9** The principle of laser line triangulation based on the projection of two laser lines.

To compensate for strip vibrations, two parallel lines can be used. A flatness defect will cause the distance between the lines to change, which can be used to separate vibrations from flatness (illustrated in Figure 9).

Since different measurement situations may require different system configurations, it is beneficial if the system geometry and performance can be changed. For instance a Shapeline system can be changed over wide ranges and be adapted to different performance requirements and the available physical space in the line.

In addition, a laser-line based flatness gauge can also measure strip width and off-center. The method has the advantages that back-lighting is not necessary and the width can be compensated for flatness.

5.4. Comparison between shape rolls and optical systems

Shape rolls and optical systems very seldom compete since they measure different type of flatness (latent vs. manifest). However, sometimes it is possible to choose a measurement location with more or less tension, and therefore a comparison can be of interest.

For cost and maintenance reasons, an optical system is always to prefer. An optical system under the right conditions also gives better performance and functionality than a shape roll as long as the tension is relatively low.

In Table 3, there is a comparison between the two techniques.

<table>
<thead>
<tr>
<th>Property</th>
<th>Laser triangulation</th>
<th>Shaperoll</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tension</td>
<td>Latent flatness can not be measured. Optical systems are not suitable for rolling mills.</td>
<td>Needs high tension. Defects not hidden by tension or developable defects are not possible to measure e.g</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Low. Normally once per year.</td>
<td>High. A spare shape roll may be required for critical applications.</td>
</tr>
<tr>
<td>----------------------</td>
<td>------------------------------</td>
<td>-------------------------------------------------------------------</td>
</tr>
<tr>
<td>Mechanics</td>
<td>No moving/rotating parts. No parts touch the strip.</td>
<td>Complicated. Rotating parts and may cause marks on the strips.</td>
</tr>
<tr>
<td>Flexibility</td>
<td>High. Can for instance be moved between lines.</td>
<td>Fixed once installed.</td>
</tr>
<tr>
<td>Resolution</td>
<td>High. 2000-4000 points in width direction. Up to 1000 profiles per second in length direction.</td>
<td>Lower and fixed to segment width. 1-4 profiles per revolution.</td>
</tr>
<tr>
<td>Flatness measurement</td>
<td>Direct. Measures actual flatness, including crossbow. Can also measure pockets, ridges, dents, edge defects etc. No „over-hearing“ between measurement points.</td>
<td>Indirect. Can only measure pressure. I-units must be calculated based on pressure on roll segments. Always some „over-hearing“ between segments.</td>
</tr>
<tr>
<td>Width and centerline</td>
<td>Possible. The width measure can also be compensated for material flatness.</td>
<td>Not possible.</td>
</tr>
<tr>
<td>Software</td>
<td>Highly flexible with many display and setting functions. Configurable outputs.</td>
<td>More rudimentary. Designed for mill control.</td>
</tr>
<tr>
<td>Affected by aging</td>
<td>Lasers have a life-time of around 50 000 hours. Until they break, the system functions normally.</td>
<td>A worn shaperoll gives less accurate measurements. Scrap on the roll will also give erroneous results.</td>
</tr>
<tr>
<td>Measurement position</td>
<td>Important. Should be installed away from deflector rolls and in areas where the strip is transported without wave-locking or hanging. Support rolls may need to be added for a good transportation. Fully possible to measure on rubber belts. Cut sheets can be measured. Normally the line does not need to be changed.</td>
<td>Less critical as long as the tension is high enough. Depending on roll type, deflection angle may have to be constant. An installation may need extra rolls to create the correct strip pass-line.</td>
</tr>
<tr>
<td>Environment</td>
<td>Dust and steam must be limited, but is very seldom a problem. The surface need to be relatively free from liquid. Air-knives may be used to remove excessive water if in large quantities.</td>
<td>Not sensitive to dust, steam or liquid on the material surface.</td>
</tr>
<tr>
<td>Economy</td>
<td>Low investment and running costs.</td>
<td>High investment and running costs.</td>
</tr>
</tbody>
</table>

Table 3. Comparison between a shaperoll and a laser line based optical flatness measurement system.

6. Integrated optical flatness sensors

Recent developments have made it possible to develop optical flatness sensors that are fully integrated. Hence, a single sensor is all that is needed to measure flatness accurately and reliably, which was not possible only a couple of years ago.

One such sensor is Shapeline VeriFlat. Let us exemplify what an integrated sensor is capable of by studying VeriFlat. But first we need to understand the technical platform, realized thanks to recent developments in camera sensor technology and signal processing electronics.

6.1. ShapeCAT

To provide an optical flatness measurement system with sufficient performance, resolution, measurement speed and accuracy are important factors. The problem is that the combination of speed, resolution and accuracy makes it impossible to use standard camera technology. It is simply not possible to move sensor data to a computer fast enough. Yet another problem is that the computer would be choked with all the sensor data being streamed to it.
The solution for this is to use high performance sensors in combination with near-sensor computing power, or in other words, put the computing power inside the camera. An example of this approach is ShapeCAT [7]. The camera in ShapeCAT has several internal processors that in effect reduce the camera pictures to profiles. As an example, instead of sending 2 million pixels to the computer 500 times per second, 500 profiles are sent via Ethernet. The data is reduced drastically and a standard PC can handle an array of cameras without being choked. In addition, standard Ethernet hardware can be used to transfer the measured data once the profiles have been generated.

If this is combined with a high-performance image sensor that has enough resolution and light sensitivity, the basis for an integrated sensor is there.

6.2. VeriFlat

VeriFlat is a recently developed product form Shapeline based on ShapeCAT. One ShapeCAT-camera and two lasers are integrated into a sturdy aluminium tube together with computing power, measurement storage, router, switch, power-supply, cooling system, laser safety protection and GPIO (see Figure 10).

![VeriFlat](image.png)

*Figure 10 VeriFlat. All necessary electronics and optics is integrated and fixed inside the sensor.*

Thanks to this, the sensor can be hooked up to a plant network, operator workstation, speed sensor and auxiliary equipment directly. No cabinet, PLC or extra computer is required. This has the following advantages:

- The sensor can be factory adjusted and calibrated. Hence, expensive and complicated calibration equipment is not required in the plant.
- Installation is straightforward and fast.
- The sensor may be moved easily between lines or measurement positions.
- The total cost is only a fraction of a Shape-meter roll and a significantly lower than a normal, engineered optical flatness measurement system. The sensor itself is more economical and the cost for the preparations required is also substantially lower.

An integrated sensor has, however, some limitations. The geometry (size, stand-off etc.) cannot be changed and the performance is fixed. It will therefore not be suitable for all applications.

A comparison in table form is found in Table 4.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Integrated optical sensor</th>
<th>Engineered system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement width</td>
<td>Fixed (e.g. up to 2000 mm)</td>
<td>As required.</td>
</tr>
<tr>
<td>Geometry</td>
<td>Fixed</td>
<td>Flexible over wide ranges.</td>
</tr>
<tr>
<td>System configuration</td>
<td>Standard + options.</td>
<td>Flexible.</td>
</tr>
<tr>
<td>Resolution</td>
<td>Limited flexibility</td>
<td>Unlimited flexibility.</td>
</tr>
<tr>
<td>Accuracy</td>
<td>Typically 0.1-0.2 mm depending on width and line speed.</td>
<td>Micrometers to 0.5 mm depending on material width, temperature and system configuration.</td>
</tr>
</tbody>
</table>
Table 4. Comparison between an integrated flatness sensor and an engineered system.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Integrated optical sensor</th>
<th>Engineered system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient temperature</td>
<td>-5° C to +35° C</td>
<td>-25° C to +100° C with proper cooling/heating options.</td>
</tr>
<tr>
<td></td>
<td>Optional water cooling for higher temperatures</td>
<td></td>
</tr>
<tr>
<td>Environment</td>
<td>Normal processing line environment.</td>
<td>Any. Also hot-rolling and plate mills.</td>
</tr>
<tr>
<td>Material temperature</td>
<td>Up to 100° C without shielding.</td>
<td>Up to 1200° C.</td>
</tr>
<tr>
<td>Calibration</td>
<td>Not required. Pre-calibrated from factory.</td>
<td>Calibration performed at installation and then annually.</td>
</tr>
<tr>
<td>Surfaces to be measured</td>
<td>More or less anything.</td>
<td>More or less anything with tailored configuration.</td>
</tr>
<tr>
<td>Width measurement</td>
<td>Possible. Limited accuracy.</td>
<td>Possible: Accuracy depends on configuration.</td>
</tr>
<tr>
<td>Measured data</td>
<td>All types of (manifest) flatness as well as width.</td>
<td>All types of (manifest) flatness as well as width.</td>
</tr>
<tr>
<td>Vibration compensation</td>
<td>Yes</td>
<td>Yes.</td>
</tr>
<tr>
<td>Communication</td>
<td>Standardized.</td>
<td>Flexible and may be configured specifically for the customer.</td>
</tr>
<tr>
<td>Applications</td>
<td>Strip processing lines, Cut-to-length lines.</td>
<td>More or less all types of flat material.</td>
</tr>
<tr>
<td>Installation</td>
<td>Straightforward and fast. May be moved between lines easily.</td>
<td>Requires configurations and calibration on-site. A new installation is required if the sensor is moved.</td>
</tr>
</tbody>
</table>

7. Applications

In this section, we will discuss a few different application areas for the two different sensor types to illustrate the pros and cons for shape-rolls and optical sensors respectively.

There are three main areas where the sensors may be used: Support for decisions, process control/improvements and quality assurance.

7.1. Process control: Rolling mills

Shape rolls have been used extensively for cold rolling mills and there are even some trials for hot strip mills [11], even though the demands from such environment are extremely hard to meet.

In a cold rolling mill, the tension is always too high for an optical sensor. There will normally be zero manifest flatness, why this application only suits shape roll solutions.

The flatness control system utilizes a target curve (Figure 11) and tries to change roll bending, roll skew and spray cooling to minimize the difference between the target curve and the measured flatness profile. Since it is favorable for strip guiding in downstream process lines if the strip has center-buckles, the target profile is seldom a straight line (flat strip).

![Figure 11](Image)

**Figure 11** Target curve and signals from the segments displayed in a graph.
However, the strip shape measured in the rolling mill is seldom the same as the shape of the strip entering a process line. There are several reasons for this.

- Due to plastic deformation in the rolling mill, the strip temperature increases. This results in a warm coil that then cools down. Since heat radiation is larger on the outer part of the coil than the center, this will create temperature gradients and may also lead to plastic deformation due to stress inside the coil when it cools down. This is important for hot rolled coils in particular.

- The temperature profile across the width is seldom constant. The cooling effect varies and thickness profile variations lead to uneven plastic deformation during rolling. Since a temperature profile is directly correlated to the I-unit profile (section 4.2), the measured profile may be wrong.

- Shape values from the shape roll are sensitive to the shape of the roll itself. If the shape roll is worn unevenly (which it gets over time due to varying strip widths), the strip shape will not be correct.

One way to handle this is to update the target profile based on the strip shape as it is being un-coiled at the entry of the next line.

### 7.2. Process improvements: Feedback to rolling

Severe flatness defects can often be observed on the incoming side of process lines. The tension is normally low here, so the manifest part of the I-unit profile is significant.

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![Figure 12](image-url)

*Figure 12  Flatness measurement on the entry side of a process line to check incoming strip quality and feedback to e.g. hot and cold rolling.*

In this part of the line, a shape-roll will not work due to the limited tension.

### 7.3. Tension leveler control

In many lines, (e.g. CAPL, EGL, CGL, CPL and CTL) there is a tension leveler to correct for bad flatness. A tension leveler has the ability to remove waves and buckles (I-units) as well as crossbow. I-units are removed by simply stretching the strip beyond its yield point at the shortest fibers, whereas crossbow can be removed by changing the strip angle \( \alpha \) over a small diameter roll (Figure 13).
Figure 13  The relation between the top and bottom surface areas of a strip can be changed by bending the strip over a small diameter roll.

This is a possibility in all tension levelers and can usually be done automatically.

To understand why this function can take out a crossbow, we have to understand the relation between crossbow and coil-set. In Figure 14, a strip has undergone plastic deformation due to coiling. This will be more prominent in the end of the coil where the coiling radius is smallest. The result is a difference in area between the top and bottom surfaces of the strip. This area difference will cause the strip to “remember” the coiling.

When the uncoiled strip is stretched out by line tension, the area difference is still there and forces the strip to flip the curl to transverse direction, causing a crossbow. Since the area difference can be changed in a tension leveler, this crossbow can be removed by changing the angle $\alpha$ in Figure 13.

Figure 14  Coil-set may be caused by plastic deformation during coiling which will occur if the thickness of the strip is too large in relation to the yield strength. The plastic deformation creates a difference in area, which in turn will make the strip “curl”. If the strip is stretched, the coil-set will transform into crossbow, since the difference in area is still there. This area difference can be removed by bending the strip in the opposite direction in a tension leveler.

A set-up for a tension leveler application is exemplified in Figure 15. The signal fed up-stream is the crossbow gap which is used to change $\alpha$ in Figure 13.

A few notes regarding this application.

- Depending on the tension after the bridles, the set-up can be used for crossbow and possibly I-unit control.
- If a shape roll is used, it must be placed between the roll-bite of the leveler and the exit bridle. The tension after the bridle is usually too low.
- A shape-roll cannot measure and control crossbow since a crossbow will not impose a pressure profile on the roll. At the same moment the strip is bent around the roll, the crossbow will go away.
Electro galvanized steel is typically used when there are high demands for very even and thin zinc coatings, and where the galvanized steel will be treated with other coatings, such as organic coatings or painting. The main application is exterior body panels in the automotive industry. One of the specialties of the EGL is that it can also coat material/alloys that are sensitive for heat, which cannot be used in hot-dip processes.

Even if the capability to adjust the galvanizing process according to the flatness is small for this process, it is important that the strip is flat entering the galvanizing cell. There is still a need to control crossbow/flatness properties, e.g. after tension leveling. Some lines (e.g. Andritz Gravitel [12]) have the ability to modify the distance between the anodes during production. This means that the users can both protect the cells as well as optimize the coating in an efficient way if the incoming strip shape is known. Smaller distance to the electrodes will save energy, but if there is a short circuit between the strip and the anodes, the electrodes will be damaged.

By measuring strip shape before the anodes the following can be accomplished:

- Anodes can be saved, either by increasing the electrode distance or by shutting off the current if the shape is bad.
- By using an optical flatness gauge as gap-guard, the distance between the electrodes and the strip can be minimized. Energy can be saved by minimizing electrode distance for flat strips
- Since there is usually a tension leveler in these lines, flatness (crossbow) information can be used for tension leveler control.

A shape roll is not suitable in this application since latent flatness will not cause any problems in the electro galvanizing.
7.1. Cut-to-length line: Quality control and support for decisions

A cut-to-length line normally has a leveler, either before or after the shear. Before the stacker, there is usually an inspection table, where the sheets are inspected for flatness errors as well as surface defects and dimensions (Figure 17). There are several benefits from installing a flatness gauge in a cut-to-length line:

- The leveler can be adjusted based on flatness data
- An automatic flatness evaluation can be used to reject cut sheets out-of-specification or give an alarm that stops the line for manual check.
- A flatness map can be generated for every sheet. A summary of this can be reported in a bundle report where the flatness is specified for each sheet. It would even be possible to send the flatness map to the final sheet user to improve further sheet processing.

![Figure 17](image)

*Figure 17  In a cut-to-length line, an optical flatness gauge can be used for leveler adjustments, sheet rejection as well as quality assurance (bundle reports to the users).*

7.2. Summary of applications

In Table 5 the different applications are summarized in short-form.

<table>
<thead>
<tr>
<th>#</th>
<th>Type of line</th>
<th>Application</th>
<th>Optical flatness gauge</th>
<th>Shape roll</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hot-dip galvanizing line</td>
<td>Entry section for check of incoming strip shape and feedback up-stream</td>
<td>Well suited. Manifest part is usually quite large</td>
<td>Not suited unless tension is high</td>
</tr>
<tr>
<td>2</td>
<td>Tension leveler control</td>
<td>Tension leveler control</td>
<td>Well suited for crossbow control. Less useful for wavy material (I-unit profile control).</td>
<td>Should be placed between tension leveler and bridle for best performance. Cannot be used for crossbow control.</td>
</tr>
<tr>
<td>3</td>
<td>Skin-pass mill control</td>
<td>Skin-pass mill control</td>
<td>Suited for cross-bow control if there is an anti-cross-bow roll.</td>
<td>Suitable for mill skew and bending control (latent I-units)</td>
</tr>
<tr>
<td>4</td>
<td>Final quality assurance</td>
<td>Final quality assurance</td>
<td>An optimal solution is after the looper and move the sensor over the strip at strip standstill for quality assurance.</td>
<td>Not applicable.</td>
</tr>
<tr>
<td>5</td>
<td>Electro galvanizing line</td>
<td>Incoming strip shape, Tension leveler control and final quality assurance: see 1-3 above.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Gap guard</td>
<td>Gap guard</td>
<td>Very suitable for optical measurement since manifest flatness cause the problems.</td>
<td>Not suitable</td>
</tr>
</tbody>
</table>
Table 5. A summary of various applications for flatness measurement in strip lines.

<table>
<thead>
<tr>
<th>Application</th>
<th>Description</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous annealing, CAPL</td>
<td>Incoming strip shape, Tension leveler control and final quality assurance: see 1, 2 and 4 above.</td>
<td></td>
</tr>
<tr>
<td>Quench tuning</td>
<td>The defects from quenching are usually manifested (crossbow and hardening buckles). High performance is required to see small buckles.</td>
<td>Normally not useful.</td>
</tr>
<tr>
<td>Pickling line</td>
<td>Incoming strip shape, Tension leveler control and final quality assurance: see 1, 2 and 4 above.</td>
<td></td>
</tr>
<tr>
<td>Organic coating line</td>
<td>Incoming strip shape, Tension leveler control and final quality assurance: see 1, 2 and 4 above.</td>
<td></td>
</tr>
<tr>
<td>Roll leveler control</td>
<td>Well suitable since tension is zero after shear</td>
<td>Not suitable</td>
</tr>
<tr>
<td>Automatic rejection</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quality assurance/bundle reports</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cold rolling</td>
<td>Roll bending, skew and spray cooling control</td>
<td>Not suitable due to tension</td>
</tr>
</tbody>
</table>

8. CONCLUSIONS

An optical system is useful in many applications, especially since modern, integrated sensors are a lot easier to use and require less capital investments in terms of system costs as well as preparations. Since integrated sensors can be moved between lines relatively easy, they are also suitable for tests and investigations. We also believe that the advent of integrated flatness gauges can be used extensively for new application areas such as cut-to-length lines and off-line feedback to rolling mills to improve the closed loop control.

The total cost for optical gauges are considerably lower than for shape rolls. It may be as much as a magnitude, so they can be motivated in many more applications than shape rolls. However, in high tension applications such as cold rolling mills, they cannot be used unless only crossbow is of interest.

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