DR PÄR KIERKEGAARD, VICE PRESIDENT SHAPELINE AB AND MSC ANDERS HEDBERG, RESEARCH ENGINEER SSAB EMEA BORLÄNGE

OPTICAL STRIP FLATNESS AND SHAPE MEASUREMENT IN HOT STRIP MILLS

Abstract

A flatness gauge in a hot strip mill can be of great benefit if it gives the right information and is reliable. A number of different gauges have been used in the past with varying results. Steel manufacturers frequently report reliability and performance issues and a lot of gauges are not even used.

This paper describes a new flatness gauge based on laser line triangulation. We show that a high-performance sensor in combination with vibration compensation can show excellent results in a hot strip mill once the difficulties with heat-shimmering and calibration have been taken care of.

In addition, a laser line based sensor also measures ski, width, shape and off-center, why it has a potential to become a powerful and versatile tool for the steel manufacturers.

Keywords

Flatness measurement, I-units, width measurement, ShapeCAT, Hot strip shape, Flatness calibration

1. Introduction

Accurate flatness measurement under hot conditions is a challenge and often leads to inaccurate and unreliable results. Strip speed, heat shimmering, cumbersome calibration, water and moist are factors that complicates the measurement.

To overcome this, Shapeline has, in cooperation with SSAB and financing support from Sweden´s innovation agency, Vinnova, developed a system for hot band measurement based on laser lines instead of laser points or white light. This has recently become possible thanks to ShapeCAT, a novel approach based on smart-camera technology developed by Shapeline specifically for flatness measurement. ShapeCAT enables high-speed and high-resolution laser line triangulation and still maintaining excellent accuracy. In addition, the resolution provided enables strip edge-detection which is used to compute strip shape, camber, off-center and width, all in the same sensor.

The heat-shimmering effect has been reduced by moving cold air into the measurement field, which drastically improves the accuracy.

The approach is demonstrated by the installation of a full scale system in a measurement house after the exit of the last roll-stand at SSAB hot strip mill in Borlänge. A novel approach for calibration has also been developed and integrated in the measurement house that enables precision calibration under production conditions. This simplifies and shortens installation as well as calibration times drastically.

This paper first describes the measurement principle and ShapeCAT, the technical platform Shapeline utilizes laser line triangulation to realize a reliable flatness measurement sensor. Then we continue to describe the conditions in the line and how we have solved the various difficulties. Specifically, we will describe a way to calibrate the sensor during full production.

The paper is concluded with some measurement examples and how the results correlate with parameter changes in the rolling mill.

2. Laser line triangulation and ShapeCAT

In laser based triangulation, shape is retrieved by projecting one or several continuous laser line(s) across the strip width, the laser lines are observed by a camera from another angle (Figure 1). Flatness affects the shape of the laser lines and this is observed by the sensor (camera) and converted to profiles. A large number of such profiles comprise a topographical map from which I-units can be calculated and flatness evaluations can be performed.

To eliminate the effect of vibrations, two laser lines are used. A flatness defect will lead to a variation in laser line inter-distance, whereas a vibration does not. This information is used to separate vibrations and flatness.

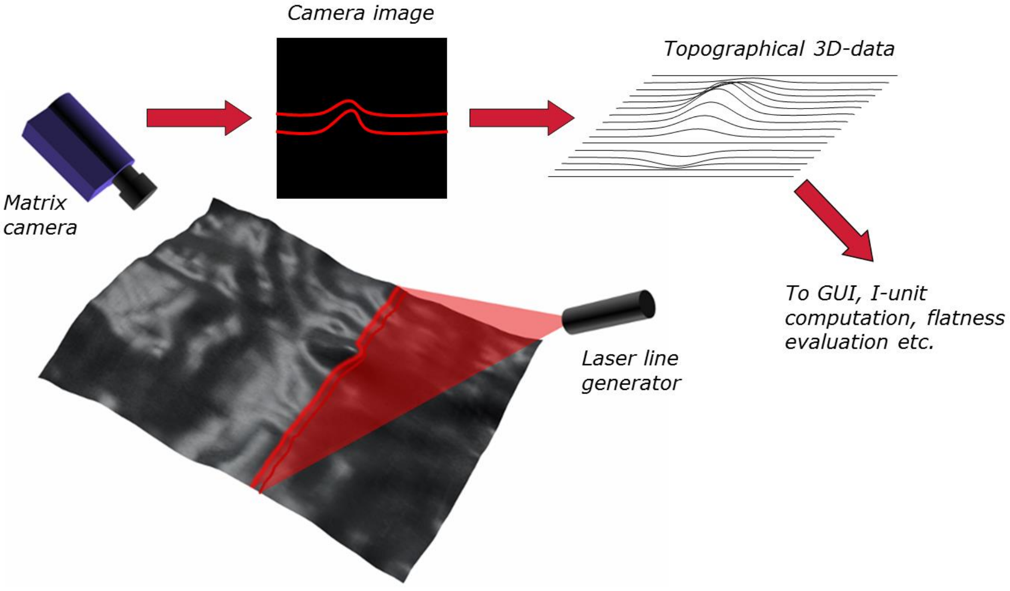


Figure 1. The principle of laser line triangulation

A challenge with laser line triangulation is to achieve a high depth-of-field (measurement range in material thickness direction), enough accuracy and small point size at the same time. High resolution images must be captured at frame rates up to more than 1 kHz. To overcome this, Shapeline has developed a new technical platform, ShapeCAT, based on a high performance smart camera [1]. With ShapeCAT, a measurement range of 200 – 400 mm can be maintained at a profile frequency of 1 kHz and still supply accurate measurements.

Some advantages with laser-line triangulation compared to competing technologies are:

- There are no moving parts at all. Moving parts in a hot environment frequently cause maintenance and reliability problems.
- Several thousand points are measured in the cross direction simultaneously. Hence strip edge-points can be measured and used to track strip off-enter position and measure width. In addition, the high resolution allows for fine-tuning of spray cooling and tuning of accelerated cooling (if the gauge is installed between the accelerated cooling and the down-coiler).

- The sharp laser lines in combination with narrow band-pass filters allow for surface reflection variations without sacrificing accuracy. The system tolerates moist, scale, temperature variations and even water on the strip to some extent.
- The high resolution cameras in ShapeCAT permit a small distance between the laser and camera, which results in a compact gauge design. This is often important since the available space in the lines is often very limited.
- The gauge can be calibrated and adjusted during production (see section 6).

A more thorough comparison between different principles for flatness measurement can be found in [2].

3. Strip temperature effects

The high temperature and heat radiation in a hot strip mill causes several problems:

- All components exposed to the strip must be cooled, either by water or by air. The gauge installed at SSAB is prepared for water cooling but air-cooling and air-purge is currently sufficient.
- Due to thermal expansion, all steel structures in the vicinity of the strip will change shape. Since the heat radiation is intermittent, there are dynamic effects during production that has to be taken into consideration. There are no fixed or stable positions in the line anywhere. The equipment has therefore been mounted on three points and is allowed to "float" during measurement.
- The self-irradiation of the strip attenuates the projected laser line. To handle this, very narrow band-pass filters have been used in combination with high-power laser line generators which work well. An alternative (which was also tested) is to utilize lasers with higher frequency, e.g. green, blue or violet lasers. The drawback of this is that the price/performance ratio is lower and the life-time is shorter. In addition, the heat-shimmering effect increases with light frequency.
- The strip temperature is not constant over the strip area. Typically edges are cooler than the center. This temperature gradient results in flatness and/or camber. To handle this, a scanning pyrometer can be used and the flatness and camber data compensated.
- For optical measurement in hot conditions, one of the largest challenges is heat-shimmering. The effect is caused by air temperature gradients between the strip surface and the sensor. The temperature differences cause the refractive index of the air to vary, which in turn cause the light rays to "bend" differently along the traveled light-path (Figure 2). Since the temperature gradients vary over time, "blobs" of measurement errors are generated. Within the blobs the noise is correlated, why averaging will not reduce the noise significantly. Since the size of the blobs can be in the same range as buckles and waves, the only way to reduce the effect is to reduce the temperature gradients. This has been done by the use of a large fan and is described in section 4.

4. Reduction of the heat-shimmering effect

To test how much and what kind of noise the heat-shimmering introduces, thin strips under tension were measured. These strips do not show any waves or buckles since all flatness is latent. Many tests were done which show similar results to what is illustrated in Figure 4 where the topography of a strip is shown for two surfaces. The top (major) part of the topographical map shows the strip and the bottom part measurement directly on a roll. As can be seen in the graph, there are deviations due to heat-shimmering of up to +/- 1.5 mm and no major difference in noise between the hot (strip) and cold (roll) surface.

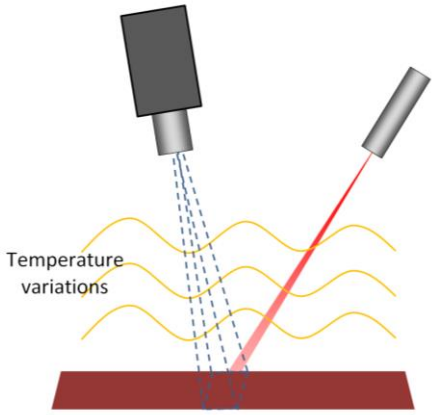


Figure 2. Air temperature variations cause the light rays to “bend” which results in optical distortions in the camera pictures.

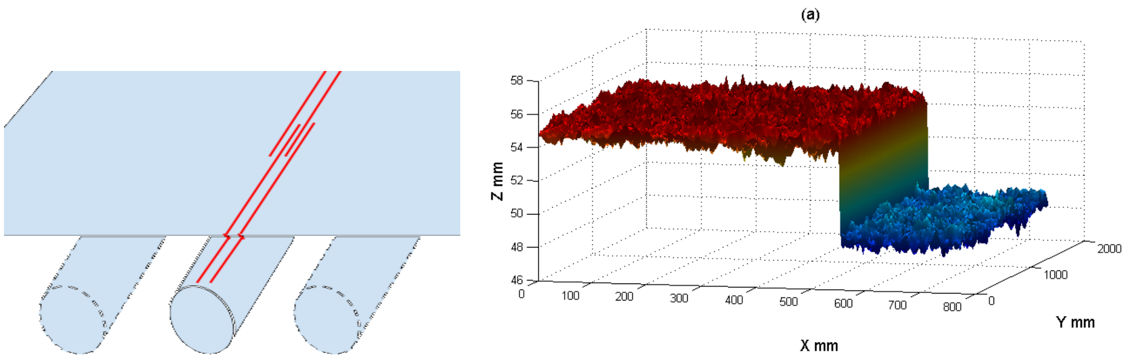


Figure 3. The strip and a supporting roll were measured at the same time (left), which resulted in two different surfaces influenced by heat-shimmering (right).

As can be seen in Figure 4, the introduced noise is not white. The measurement errors tend to cluster into “blobs” with varying sizes and shapes. This shows that the noise is correlated and cannot be reduced by averaging. The only way to deal with this is to limit the cause, the temperature gradients.

Since there is no correlation between heat shimmering and surface temperature, one may assume that the temperature gradients occur everywhere in the measurement area, not just close to the hot strip surface. This was also verified by applying high-intensity compressed air limited to the strip surface, which did not give any significant improvement. A number of other trials using compressed air were also done, but the effect was limited due to varying air-flow in different areas.

To remove all the air in the measurement area, a 1 m diameter, 15 kW fan was installed perpendicular to the strip transport direction (Figure 5). The fan effectively moves relatively cold air from the neighbor areas into the space between the strip and the bottom of the measurement house. A frequency converter enabled speed regulation of the fan.

By varying the fan power during the measurement, the effect of the fan could be monitored, which is shown in Figure 6. As can be seen, the air-flow from the fan reduces heat-shimmering and the measurement accuracy is significantly improved.

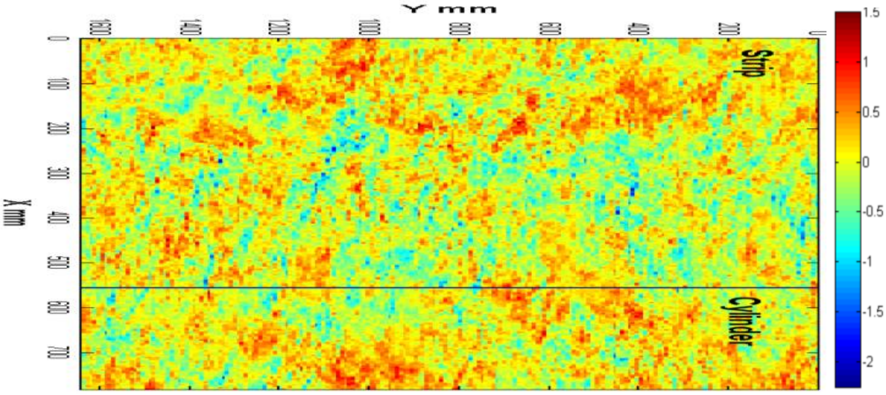


Figure 4. The figure shows a top-view of the measured strip from Figure 3. The two surfaces have been aligned for better visibility.

Figure 5. The fan underneath the measurement house.

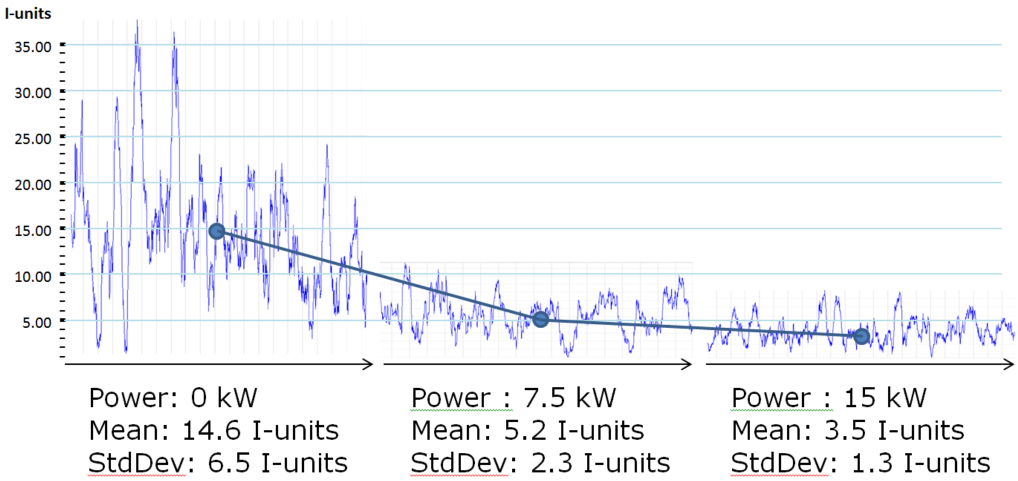


Figure 6. I-units introduced by heat-shimmering. Three different measurements were done on the same coil with a change of fan power between the measurements.

5. SSAB:s hot strip mill

The hot strip mill of SSAB consists of two furnaces, a rougher, coil-box, shear, a 6-stand finishing mill, a thickness gauge, a measurement house, accelerated cooling/quench and a down-coiler (Figure 7). The mill is capable of producing 2.8 MTonnes per year of material from mild steel to extremely hard Hardox 550 directly in the hot strip mill. It can therefore run with a wide range of parameter settings. Strip thickness also varies over wide ranges, from 1.8 to 16 mm.

The mill produces strips up to 1600 mm wide and a speed of up to 15 m/s. The roller table is 2000 mm wide to accommodate for strip centerline variations. There are side-guides to keep the strip on the roller table.

The strip flatness can be affected by roll bending and skew in mill-stands 2 to 6, but in reality, only the last two stands are used for flatness control where the parameters are changed through the ABB control system. During the initial 90 meters of strip, the operators can get a perception of the flatness by direct observation of the strip a few meters after stand 6. If it's necessary they can change the setting of the skew and bending to try to achieve a better flatness of the strip. It is, however, very difficult to get a good picture of the flatness visually and react quickly enough. A rapid, automatic measurement has the potential to help the operators do this faster and more accurate.

The experimental flatness gauge has been installed inside the measurement house, where there is also a surface defect detection system and a width gauge. The house is air-conditioned, so water cooling has not been necessary.

Figure 7. HSM with measurement house (from SSAB)

6. The measurement set-up and calibration

The measurement gauge used to test the concept consists of the following parts:

- A mechanical supporting structure mounted onto the floor
- A sensor frame with cameras and lasers, hinged in one end
- A calibration column for in-house calibration
- Four holes through the floor in the measurement house for the light beams
- A large fan for reduction of heat-shimmering (see Figure 5)

The sensor frame is based on two ShapeCAT-cameras and two double line laser projectors. Since the equipment is installed inside the measurement house in the line (Figure 7), an air-purge using low-pressurized air is enough to protect the sensor components.

The gauge is capable of measuring up to 1000 profiles per second with a resolution of almost 4000 points per profile. It has a depth range of up to 400 mm and measures 2 m width. The final, filtered resolution is 25*25 mm at 15 m/s with a theoretical (cold) accuracy of 50 micrometers, 2σ. The dynamic, hot accuracy will depend completely on how the measurement conditions can be handled, not on the accuracy of the gauge.

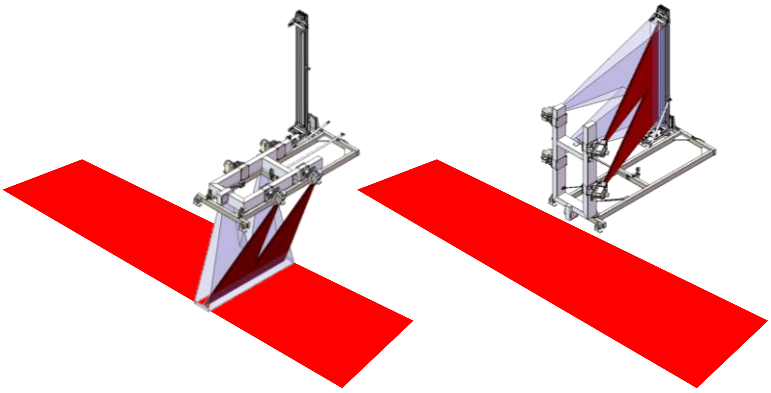


Figure 8. Schematic arrangement of the measurement system. The left figure shows measurement position and the right shows calibration position.

Width, and off-center are measured with full resolution and the accuracy is about 0.5 mm, 2σ.

Calibration can be done at any time, which has been very useful both during the installation and the development. Since calibration and system adjustments can be done while the line is in operation, it is done under the same conditions (hot) as for the measurements. No waiting time for the line to cool down and no dirty, hazardous work on or nearby the roller table has been necessary.

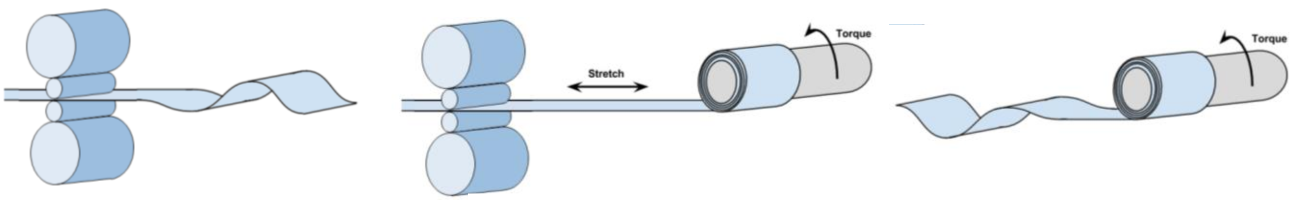
7. Measurements

A large number of strips have been measured successfully in various resolutions and conditions. Strip data is clear and the effect of heat shimmering is limited.

The strip can be divided into three different parts. The first part includes the strip head and is tension free. The second part of the strip is measured under tension, after the strip head has reached the pinch roll before the coiler, Then most flatness is transformed from manifest to latent and the strip looks flat unless there are severe flatness defects. For the last part of the measurement, the strip is again without tension after the tail of the strip is released from the rolling mill (Figure 9). An example measurement is shown in Figure 10. The point where the manifest flatness is transformed into latent is marked and clearly visible. One buckle has survived the tension and indicates a high I-unit value.

In Figure 11, the measurement of the final, tail part of the strip is shown. Once the tension is released, up to 30 mm buckles and waves become visible.

The measured data was also correlated with the roll bending and skew parameters in the mill.



First 75 m without tension   Tension applied   Last 10 m without tension

Figure 9. The three rolling phases.

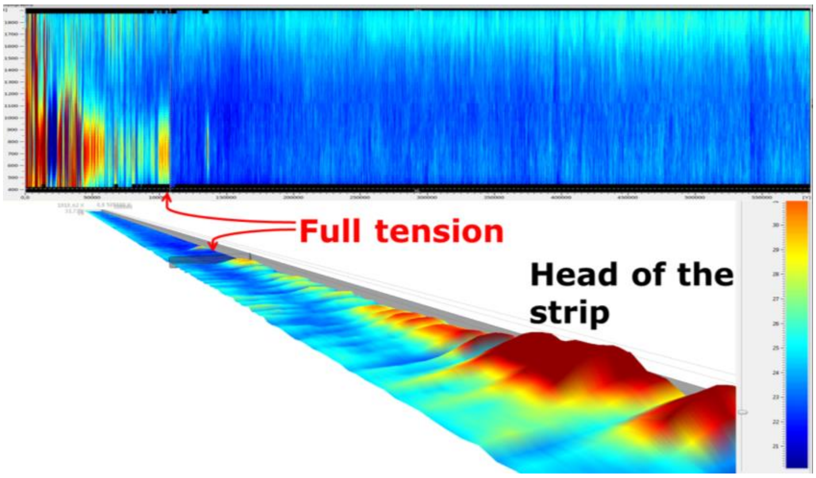


Figure 10. An example measurement. The top graph shows color coaded topography for the major part of the strip. Underneath is a 3D-graph of the same data seen from strip head position.

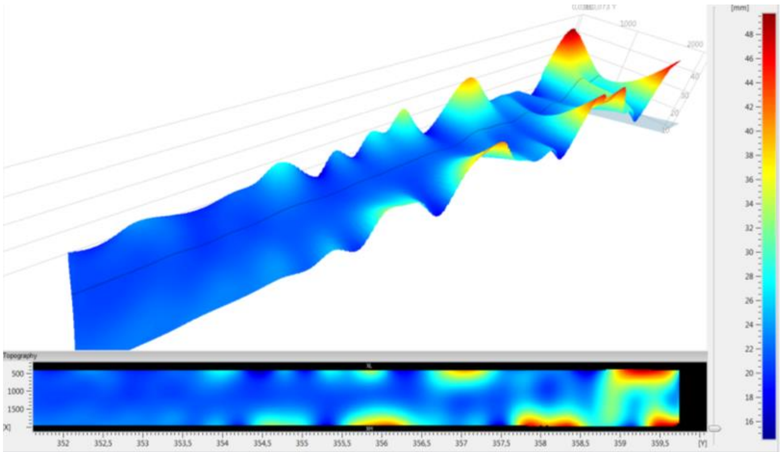


Figure 11. A zoomed in view of the strip tail

Figure 12 shows raw data at full resolution for the first few meters of strip and as can be seen; the influence of heat-shimmering is limited. The first part of the strip has some outliers (black sports) due to water droplets. They are removed by filtering at a later stage.

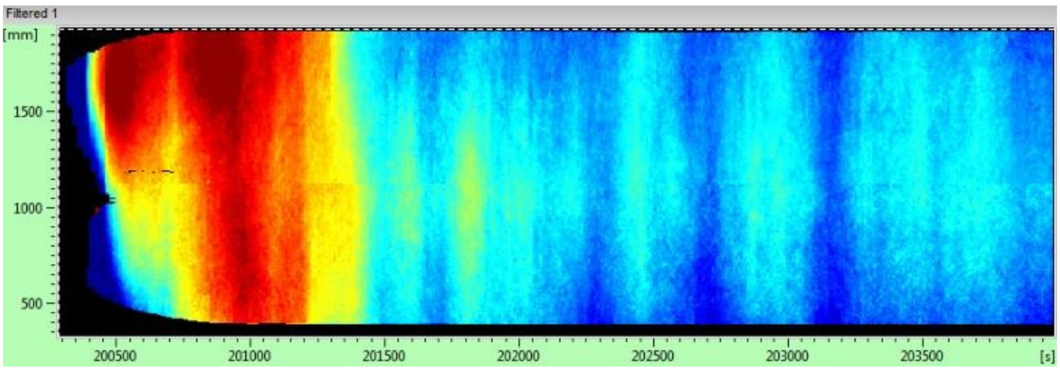


Figure 12. The strip head.

By detecting the edge-points of the strip (which is done in full resolution), the strip width can be measured. Since the strip flatness is measured at the same time, width can be compensated for flatness. As an example, Figure 13 shows a strip width graph from a strip head. The strip head is significantly narrower than the rest of the strip, which is also shown in the left part of Figure 12.

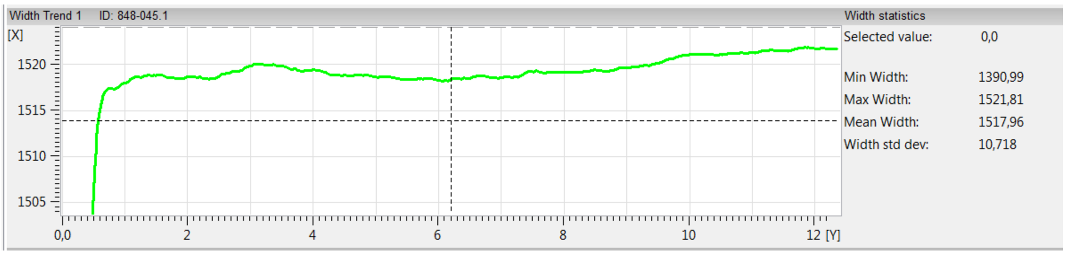


Figure 13. Strip width graph from a strip head

In principle, the gauge is also capable of measuring camber (hooked strip edges), which are clearly visible in the user interface. However, currently there is no possibility to separate camber from side-shifts, why more information must be incorporated to handle this.

8. Reactions on rolling mill parameter changes

To see how the measurements react on roll bending changes, some initial tests have been done. The rolling mill skew and bending were changed for mill-stands 5 and 6. As can be seen in Figure 14, the changes are clearly visible. At the time of writing this paper these tests have only commenced, why no model or deeper analysis had yet been done.

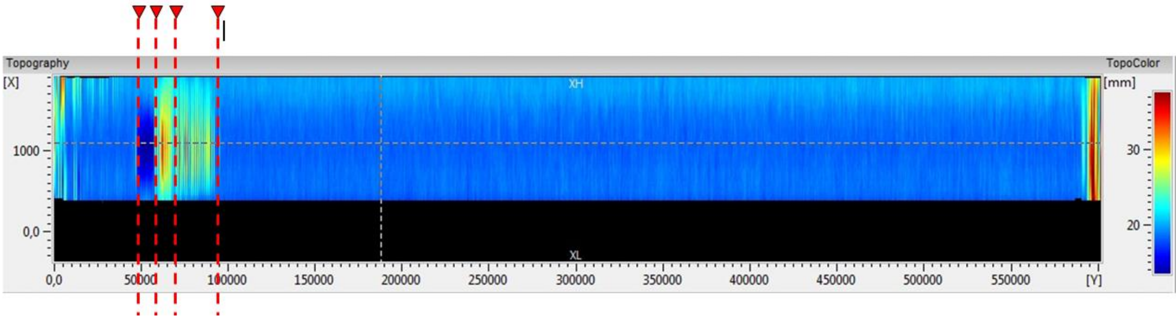


Figure 14. A strip where the mill-stand changes Triangles indicate where the rolling mill parameters were changed.

9. Potential benefits

From SSAB:s perspective, the benefits from the measurement are different for the different parts of the strip (Table 1).

Measured property	Strip section		
	Head	*Center*	*Tail*
I-units	Mill skew and bend can be adjusted to produce flatter strips	Supervision and some adjustments	Quality assurance
Crossbow	Compensation of width-data	Compensation of width-data	Compensation of width-data
Ski	Ski-down is not wanted and may cause strip stop. Mill can be adjusted to limit this. Ski-up	Not applicable	Less of a problem

	may cause problems at the feeder and folding in the coiler.		
Head and tail shape	Crop-shear optimization	Not applicable	Crop-shear optimization
Width	Crop-shear optimization, edge trimming	Quality assurance, edge trimming	Crop-shear optimization, edge trimming

Table 1. Different types of data can be used for various purposes for the three different parts of the strip.

The results are very promising and the gauge has already shown several possibilities which were not expected when the project was commenced. For example, mill parameter changes can be observed with great detail and the width measurements seem to be more reliable than the alternative width gauges.

To augment the benefits, there are two separate user interfaces, one for the operators, focusing on real-time and direct process control and one for process and quality personnel, which contains much more and detailed information.

10. Conclusions

We have described how to use laser line triangulation with ShapeCAT smart-camera technology to measure different types of flatness, as well as width and off-center in a hot strip mill. We have also described how to calibrate the system under production conditions and how to create the right conditions for measurement by reducing heat-shimmering.

By several examples, we have shown that the data retrieved are good and reliable enough to be used for mill control as well as for shape supervision. The gauge is capable of providing accurate flatness data at high resolution as well as sub-mm width data even for high-speed hot strip mills.

Since no work needs to be done near the roller-table, the solution is safe and calibration as well as maintenance can be done efficiently and independent on production stops. The gauge has potential to be used for direct mill control as well as being a powerful tool for the mill operators.

11. Acknowledgements

We would like to thank the operation people at the hot strip mill in Borlänge who have been friendly and helpful throughout the project and Emil Ekblad who has done an excellent job setting up the system and performed endless of measurements as well as analyzed them.

A special thanks to Vinnova, the Swedish Innovation agency for financial support during this project.

12. References

[1] Dr Pär Kierkegaard and M. Sc. Lars-Åke Classon, A new generation optical flatness measurement systems, Iron and Steel Technology, Dec. 2015.

[2] Dr Pär Kierkegaard, Automated optical flatness measurement for flat metal products, Proceedings 50´th Rolling Mill Seminar – Processes, Rolled and Coated Products, 18-21 November, Ouro Preto, MG, Brazil.