Optical strip flatness and shape measurement in Hot Strip Mills

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Keywords: Hot strip rolling, Accelerated laminar cooling, Laser line triangulation, Flatness measurement

INTRODUCTION

SSAB is a Swedish company in the steel sector and in many ways a pioneer in the production of world-leading steel grades such as Hardox for wear plates, Strenx for performance steel, Docol for automotive steel. SSAB is also a world-leader in the ambition to make steel production and use sustainable. One example is SSAB’s target to use hydrogen to produce fossil free steel in 2035. Another example is to provide material and services for making lighter and more environmentally friendly constructions. A base for this is Advanced High-Strength Steels (AHSS) and Quenched & Tempered Steels (Q&T). Since year 2012, SSAB produces Hardox directly in the hot strip mill, a great challenge in terms of direct quench capacity and maintaining material properties and shape over strip width and length. The benefit is both economical (one processing step is omitted) and environmental (less energy and capacity is required). It has turned out that flatness is the most important and difficult property to master in a direct quench line.

Shapeline is a Swedish company focused on in-line optical measurement of flatness and other dimensions of flat metal. Shapeline has supplied flatness measurement systems since 1997 and now has a large number of systems in the world’s steel and metal industries. Shapeline’s ambition is to develop new technical solutions which deliver performance, reliability and information required by a developing steel and metal industry.

In year 2014, Shapeline and SSAB commenced a cooperation to develop a concept for flatness measurement which could be used to analyze how flatness affects laminar cooling and how incoming flatness transforms into outgoing flatness after the accelerated laminar cooling. The project, Opticool, has had financing support from Sweden’s innovation agency, Vinnova.

The first step in this was to develop means for reliable and high performance flatness measurement after the mill and the second step to measure both before and after laminar cooling to understand the mechanisms behind the flatness transformations.

The first part of the project to realize the flatness gauge for hot environments was reported by Kierkegaard and Hedberg in an earlier paper [5]. This paper focuses on how the two gauges have been used to understand how the laminar cooling affects flatness.

BACKGROUND

Flatness measurement in hot strip mills has been used for decades and most mills have some kind of flatness measurement device that delivers data to the AGC. Most systems in the past have been based on a limited number of discrete points, typically 3 or 5.

There are several principles which can be used for this, whereof laser line triangulation is one such method. Laser line triangulation is a robust method and accurate where high resolution data can be obtained in the width, length and height directions [1], [2], [4]. However, laser line triangulation is computationally intensive compared to competing techniques. A hot strip mill is an example of a high-speed line and for analysis of the accelerated laminar cooling, high resolution is required both in width and length direction which puts very high requirements on the measurement system. This has been solved and the resulting product, VeriShape, also handles the hot environment well.

SSAB HOT STRIP LINE IN BORLÄNGE

The hot strip mill in Borlänge originates from 1961 and has been modernized several times over the years. The line is compact, flexible and capable of producing a large number of different qualities. A major re-vamp was done in 2011 when the new cooling section in the hot strip mill was installed and became operational (Figure 1 and Figure 2).
The cooling line is 60 m long and maximum cooling capacity is 14,300 m³/h. The amount of water through each header is fully and independently controlled. Before the strip arrives, a model calculates the required amount of water as a function of incoming strip temperature, speed, thickness and other parameters. The water flow is then adjusted at the working point in the main section of the cooling line to have the correct flow before the strip arrives. After the strip has reached the down-coiler pyrometer, the feedback control fine-tunes the correct amount of needed water in the trimming zone. The feedback control continuously re-calculates and adjusts the required amount of water based on acceleration/deceleration and other varying parameters. Furthermore, different strip qualities need different cooling strategies. The cooling strategy describes how the water is distributed over the length in the cooling section. The strategy can for instance be to create a high cooling gradient over the strip length or create a low, slower gradient depending on final strip properties.

![Figure 1. SSAB hot strip line in Borlänge](image1)

![Figure 2. The layout of SSAB:s hot strip mill.](image2)

**THE VERISHAPE FLATNESS MEASUREMENT SYSTEMS**

The line has been equipped with two Shapeline VeriShape systems, one in the gauge house directly after the mill and one directly after the laminar cooling (see Figure 2 and Figure 3).

![Figure 3. The two VeriShape systems. Left: The system in the gauge house. Right: The system after the laminar cooling.](image3)
The VeriShape systems are developed specifically for hot strip measurements and have the following key characteristics:

- The systems are based on ShapeCAT, a camera/laser technology developed by Shapeline for high performance flatness measurement. Specifically, the technology delivers high-resolution data in length, width and height directions. Over 2000 measurement points cover the strip width and the length resolution is 25 mm, even for a hot strip mill running at 25 m/s.
- The gauges detect strip edges and also deliver off-center position to compensate strip side-shifts as well as flatness compensated width measurement.
- To reduce the effect of heat-shimmering, the hot air between the material and the gauge is removed by the use of a 15 kW fan.
- Self-adjusting mechanics are used to eliminate the effect of shape variations in the gauge house due to temperature gradients. Thanks to this, calibration/adjustments are only required 1-2 times per year.
- The gauge is designed to eliminate the need for line-stops both during installation, service/maintenance and calibration. No work is ever required on the roller table.

For further details regarding VeriShape, see [3] and [4].

To utilize the information from the gauges optimally, they are connected to each other and data from both gauges can be displayed simultaneously in the same user interface, both during production and off-line. In off-line mode, the software automatically finds both measurement files related to a strip ID and displays topographical data, I-unit data and the difference between the two measurements on the same screen. Both 1D, 2D and 3D-data are displayed.

**FLATNESS IN HOT STRIP MILLS**

Flatness can be subdivided in a few different categories (see also Figure 4).

- **Crossbow** is a flatness defect purely in the width direction. It is normally caused by an area difference between the top and bottom strip surfaces. The area difference can occur due to plastic deformation during coiling [2], [4], internal stresses or variation of Martensitic content between the two surfaces. Crossbow is not affected by strip tension.
- **Ski up/down** can be the result of speed differences between the work-rolls. Especially ski-down can cause roll damages, wavy strip and in the worst case, line-stops due to jammed strips.
- **Parallel waves** are waves which have equal fiber length over the width. It is caused by plastic deformation at some position in the line. One source may be a ski-down where the head of the strip hits the rolls. Parallel waves disappear immediately when strip tension is applied, but may show up again when tension is released.
- **Edge waves/center buckles** are caused by varying fiber length over the width. If the fibers in the strip center are longer than at the edges, the strip will have center-buckles. Buckles or waves may show up anywhere in the width direction depending on the distribution of the fiber length. This is normally referred to as I-unit profiles [4]. Edge waves and center-buckles may exist at the same time.

![Figure 4. 3D-plots of typical flatness from a hot strip mill. From left to right: 1. Crossbow or gutter. 2. Ski up. 3. Parallel waves. 4. Edge waves (left part) and center buckles (right part). From true hot-strip measurements.](image)

**Temperature effects**

Waves and buckles may also originate from temperature profiles across the width due to thermal expansion. Since the thermal expansion factor of steel is 11 – 12.5 μm/m°K, center buckles caused by a warmer strip center than the edges can be considerable. The temperature difference can easily be 40 – 50°K, resulting in around 50 I-units. At 50 I-units, a 1 m long wave has a wave height of 14 mm.

**MEASUREMENT RESULTS AND OBSERVATIONS**
A large number of strips have been measured by both systems. More or less the complete production of the hot strip mill has been observed since March 2016 for the gauge after the mill and since February 2018 for the gauge after laminar cooling. The line produces approximately 2.2 million tons per year.

The example strips reported in this paper have larger flatness deviations than most strips to illustrate the behavior of the laminar cooling more clearly.

Figure 5 shows a strip with a combination of crossbow and buckles (I-units) before and after the laminar cooling. Two areas with different strip shape have been marked with dotted lines, A1 and A2. In the following, we will take a look at the crossbow and I-units of the strip separately, starting with crossbow.

**Crossbow**

Figure 6 displays the strip with the waves taken out. This displays the pure crossbow shape of the strip. There is also a differential map at the bottom which displays the shape contribution from the laminar cooling.

To show the crossbow even clearer, Figure 7 shows the crossbow in each area averaged over the length. This drastically reduce noise and visualizes a slight crossbow after the mill, bending up in the first part of the strip and then bending down after about 30 m of strip.

![Figure 5](image.png)

Figure 5. A part from the user interface showing topographical maps of the measured strips after the mill (top) and after laminar cooling (bottom). The legends to the right show what the colors represent in millimeters.
Figure 6. Extracted crossbow data from the topographical data in Figure 5. The lower map shows the difference from the entry of the laminar cooling to the exit which is the crossbow added by the laminar cooling. As can be seen, most of the final crossbow is created in the laminar cooling.

We can observe the following.

- A small crossbow is transformed to a much larger crossbow after the laminar cooling.
- The sign of the crossbow is the same before and after laminar cooling.
- The gutter-shape of the strip keeps liquids on the surface easier (Figure 8).

Figure 7. Crossbow of areas A1 and A2 of the two measurements. As can be seen, the crossbow is amplified in the laminar cooling.
Fluid stays on the strip due to gutter-shaped crossbow.

I-units

If we now do the same comparison for I-units, the results are a bit different. In Figure 9, I-units are shown for the same strip. As can be seen, the I-units are considerable in the initial part of the strip (A1), whereas the I-units in rest of the strip is close to zero, both before and after laminar cooling. If we plot the accumulated I-unit profiles for the area A1, we will again see that flatness before the laminar cooling comes out larger after laminar cooling (Figure 10). However, the difference is not very prominent. This can also be observed in the difference graph.

![Image of extracted I-unit maps](image.png)

Figure 9. Extracted I-unit maps from the same coil as is shown in Figure 5. The head of the strip has considerable I-units, whereas the rest of the strip is nearly without waves and buckles.
Figure 10. I-unit profiles from area A1. The I-units are slightly higher after laminar cooling than before, but the shape is surprisingly well preserved.

The remaining I-unit in area A2 and the rest of the strip is negligible. It is well below 1 I-unit after the laminar cooling and a little higher after the mill. These I-unit values can be explained by the effect of heat-shimmering (noise) and may not be real flatness defects.

From the above figures, one may believe that a flat strip going into the laminar cooling also comes out flat. This is indeed the case and illustrated in Figure 11 and Figure 12. Areas with flatness issues after the mill come out with worse flatness after laminar cooling. Flat areas remain flat.

This effect was observed systematically. The displayed results are only examples.

Figure 11. Topographical data of one coil with three relatively flat areas which are preserved through the laminar cooling. Again, the areas with flatness problems come out of the laminar cooling with bigger flatness defects.
The VeriShape system after the mill has been delivering data since March 2016. The system has proven to be reliable and been continuously improved. However, the real benefits for the mill started to show up when the second gauge after laminar cooling started to deliver data in February 2018. The power of the combination has been illustrated in this paper, where the two systems act as one and report the flatness contribution from the laminar cooling.

One important result is that material which is flat when it enters the laminar cooling comes out flat, whereas both I-units and especially crossbow are amplified in the laminar cooling. The reason is most likely that a flat strip also results in an even cooling power over the area. Flatness variations will result in a more uneven water flow and therefore a varying cooling power. It is therefore crucial to control the finishing mill to produce flat strips.

We have not yet analyzed the effects on the distribution of the material properties as a consequence of flatness and the resulting varying cooling effects. This is a topic for future research.

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