AUTOMATED OPTICAL FLATNESS MEASUREMENT FOR FLAT METAL PRODUCTS[1]

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Abstract

This paper presents a laser based flatness gauge and how it can be integrated in steel and metal production lines. The reasons why flatness measurement is important are explained, the aim with and benefits from flatness measurements brought to light. We describe the laser line triangulation principle and Shapeline systems' strengths compared to competing techniques in terms of robustness and performance. We discuss what kind of clear and immediately usable information the operator should see in real time, and also information analyzing the results for longer term purpose. Finally, based on some 75 customer cases, we describe benefits, quantitative as well as qualitative and give some examples from real customer cases.

Keywords: Flatness measurement; Quality assurance; Flat metal products.

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1 INTRODUCTION

Today, more and more steel producers aim for high yield strength steels. New lines are built and old lines upgraded. The market situation for these kinds of steels is currently better than for normal steel. The new plants are also designed for higher productivity and thinner, wider material than those in the past. Each one of these factors makes it more difficult to produce material with a flatness that can be accepted by the steel users. Thus, end-user requirements and flatness related costs increase.

To improve flatness, make correct decisions and assure shape quality of flat metal products, the flatness must be measured reliably and with the required accuracy. This has shown to be non-trivial, and a larger scope than the measurement system itself must be addressed, such as material transportation, drift, temperature variations and requirements based on how the measurement data will be used, now and in the future. It is important to understand all these factors to tailor a measurement function which satisfies the requirements specified. However, once this is done, a flatness measurement function can be very useful and pay for itself in a matter of weeks or months.

2 MATERIALS AND METHODS; 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 1). It is normally 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. The bending can be observed by a matrix camera. The line is then projected in the camera image across the picture 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. This makes the measurement precise, but also independent on the actual intensity. Since the intensity itself is not important, only the position of the line which contributes to the robustness of the method.

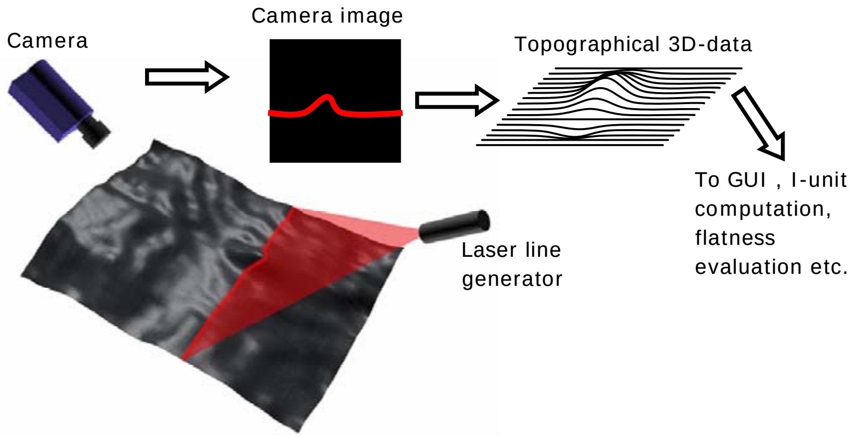


Figure 1. The principle of laser line triangulation.

Since every column in the camera results in one measurement point, the point density across the width is high. It is therefore possible to detect small buckles and waves and also material edges with reasonable accuracy. Since all points are acquired at the same time instant, vibrations do not affect individual profiles.

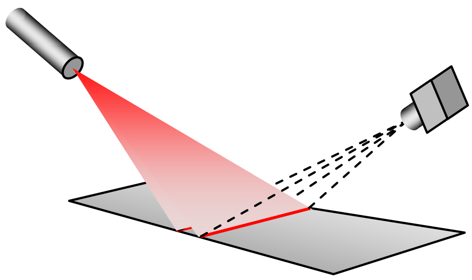
However, to build up a complete topographical map a large number of profiles need to be combined over the time elapsed from strip/plate head to tail. Hence, in material length direction, the vibrations need to be compensated for.

2.1 Extending the Method to Gradient Computation

As mentioned above, the described principle has the limitation that vibrations and flatness cannot be properly separated. If the vibration frequency is different from the frequency of the waviness, it is possible to separate the two by the use of the Fourier transform. This has been done with success when the frequency of the flatness deviation is different from the vibration. If the frequencies are similar, it will be useless.

A more universal method is to project two laser lines after each other in transport direction to measure local surface gradient as illustrated in Figure 2. A shape defect always gives a change in the local gradient, whereas a vibration does not.

In fact, also an elastic deformation gives no or very limited gradient change unless the material reshape (the buckles move). Therefore, the method also compensates for elastic deformation to some extent.



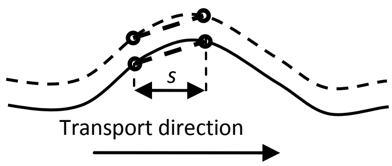


Figure 2. The double laser line triangulation principle.

The principle is described in more detail by Kierkegaard and Andin.[1]

2.2 Features

Laser line triangulation has a number of attractive features. Some of the more important are:

- High resolution in the width direction enables material edge detection. This can be used for width measurement, but also helps to track the material when it moves sideways.
- The laser light has one single frequency. By mounting a matched, narrow filter in front of the camera, we can effectively block out all non-relevant light. Hence, the measurement is not disturbed by ambient light.
- The measurement is focused to one single position in material length direction. Due to this, the sensor can be compact and necessary transport improvements can be focused to the area around this point only. It also simplifies calibration.

- The geometry is flexible. Depending on available space and performance requirements, different optics and angles can be used.
- The method can be used for a wide variety of surfaces. Specifically, rolled surfaces have a “scratched” structure in the length direction on micro-level which spreads an incident light-ray like a hand-fan (see Figure 3). This spreading enables laser-based measurements even on bright, shiny material. If the geometry is set up correctly, the same system can handle specular as well as matte surfaces without parameter changes. This is described in detail by Kierkegaard[2,3] and illustrated in Figure 4.

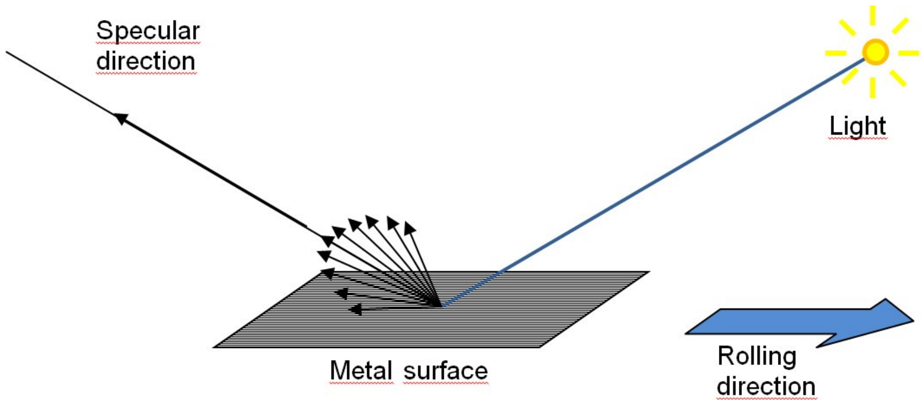


Figure 3. An incident light-ray spreads in a hand-fan pattern which evens out the intensity in the width direction.

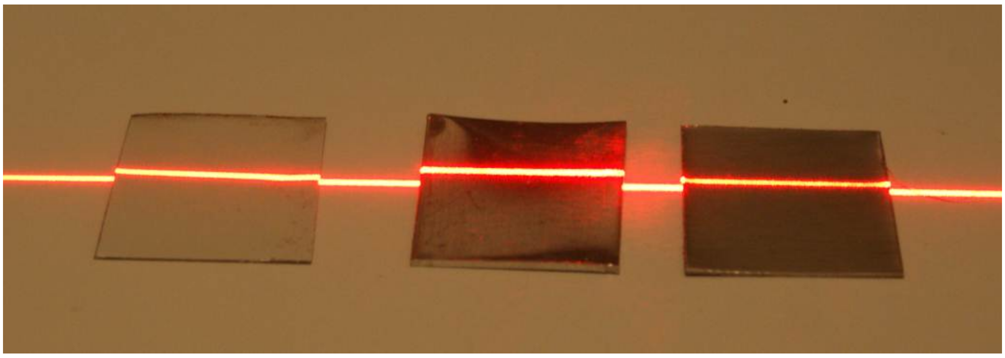


Figure 4. Three different surfaces illuminated with a laser line. From left to right: Organic coated (white) galvanized steel sheet, bright stainless steel and aluminum sheet. The viewing angle has been optimized for the bright stainless steel sheet.

2.3 Alternative Techniques

There are two main alternative techniques for measuring manifest flatness, point sensor systems based on triangulation and white light projection methods. Both exist in a multitude of configurations and have been used for a long time.
The advantage for laser-line triangulation over point based systems is the point density in the width direction. The resolution of a point-based system is the number of sensors which is limited due to physical as well as economy whereas the limitation for a laser-line triangulation system is the number of cameras and the camera resolution. Typically, point based systems have 5-25 points whereas a laser-line system can have 4000 points or more. The advantage with high width resolution is illustrated in Figure 5. There are two main cases: peak detection error and edge detection error. Both errors will also affect the error in estimated crossbow value.

As a matter of fact, a point-based system does not fulfill the requirements defined in international standards since a resolution of 10-25 mm is required for this as described by Kierkegaard.[2] Especially the fact that the edges cannot be detected and measured properly can be bothersome. Edge waves are important to measure for many metal producers.

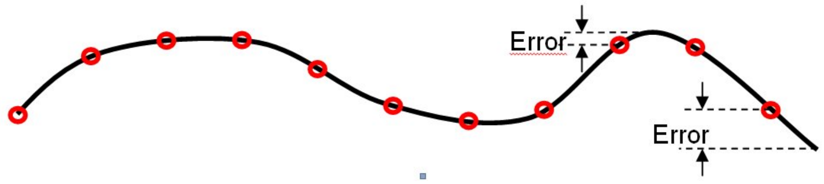


Figure 5. Error caused by under-sampling in the width direction. The extreme values of the flatness will not be detected, and therefore the error can be several mm unless the point density is increased.

Structured white light[4,5] does not suffer from the above problems since the resolution can be high. However, laser line triangulation still has advantages. A laser line is narrow and distinct, which means that it is not affected by reflectivity variations of the measured surface, glossy surfaces or reflections from ambient light (since the majority of the light has a wavelength which differs from the laser line). This is illustrated in 0 and 0 where three different steel surfaces have been illuminated both with structured light and a laser line. Krambeer et al.[5] describe a method to overcome the problem of glossiness by observing a reflected image instead of the surface directly. This principle seems to handle glossy surfaces as long as the required screen can be kept clean and without damages. However, the problem with distorted data due to locally varying reflectivity persists.

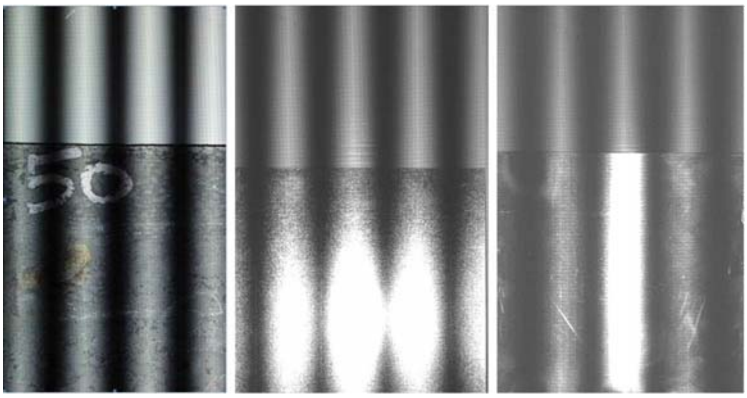


Figure 6. Three different surfaces illuminated structured light. From left to right: Quarto plate with some painted text, a galvanized steel sheet and a ground steel sheet. The top parts of the pictures show the reflection on a painted surface for reference. As illustrated, the reflected light depends heavily on the reflectivity of the surface illuminated.

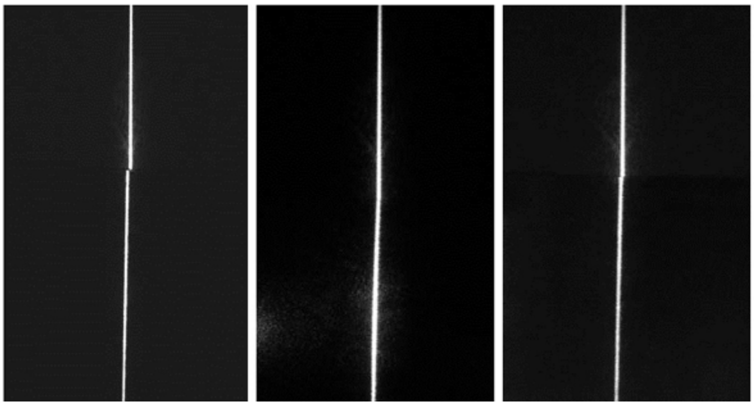


Figure 7. The same three different surfaces illuminated with laser light. In spite of the large variation of the surface reflectivity, the pictures look almost the same. This shows one of the strengths of the laser line triangulation principle.

3 RESULTS

Once the technique has been chosen, it has to be implemented into a measurement system and integrated into the production line. Shapeline has experience from this from over 70 installations over more than 15 years. The method has shown itself to be versatile and robust. In this section, we will give some examples.

3.1 Geometry

A laser line system is flexible and the geometry can be changed depending on available space and other circumstances in the line. It can be compact to save space but also adapted in other ways. Two examples are shown in Figure 8.

Figure 8. Left: The lasers have been integrated onto the leveler (behind the steel bars) and the cameras far away (on the blue structure in the front) to allow for extreme ski of the plates. Still the point of measurement can be chosen to be on an optimal distance from the leveler. From SSAB, Oxelösund, Sweden. **Right:** The lasers, cameras, cooling system and electronics are integrated on a common platform, protected by heat-shields underneath and accessible through stairs from both sides of the line. All components are accessible and replaceable also when the line is running. At the measurement position (where the laser lines are), the plate is supported by non-driven support rolls to eliminate elastic deformation of the plates. From Nippon Steel, Oita, Japan.

The sensors from Shapeline have a built-in flexibility regarding geometry as well as performance. By carefully selecting the geometry, a wide variety of applications can be realized. Laser line triangulation has successively been applied by Shapeline in the following applications:

- Precision strips, stainless and carbon from 10 mm to 900 mm wide both in inspection lines (up to 2 m/s) and hardening lines (6-10 m/min).
- Hot-dip galvanizing lines for crossbow measurement and tension leveler control. Width up to 1800 mm. The same sensor measures both skin-pass milled and non-skin-pass milled surfaces without problems even though the surfaces are very different in glossiness.
- Electro-galvanizing lines for shape control before galvanizing and automatic control of tension leveler. Width up to 2000 mm.
- Continuous annealing lines up to 1800 mm width for process control and quality assurance.
- Cut-to-length/shearing lines with a wide variety of materials.
- Silicon steel. For edge wave, dent and buckle detection.
- Steel plate leveling, shearing and quality inspection up to 5600 mm width.
- Hot-strip applications up to 2000 mm width and material temperatures up to 1000 °C with 15 m/s transport speed.
- Aluminum strip, sheet and plate measurement of various dimensions up to 200 mm thickness and over 2 m width.

Surface conditions are very different from black scale, moist, oiled, different coatings, bright, stainless, normalized, etc. The same basic components and software have been used everywhere, whereas optical parameters such as focal distance, focal length, laser fan-angle, aperture, shutter-speed, viewing and incident angles, etc. are adapted to the respective application. This has enabled a large variety of geometries and performances, adapted to the respective applications.
Point resolutions from sub-mm range up to 25 mm (in length and width directions) and accuracies from micrometer to approx. 0.5 mm have been reached, higher accuracies for special steel, lower for hot applications.

3.2 Speed Information

In plate applications, it can be difficult to get correct speed information. Sectioned roller tables with different speeds, levelers, slippage during acceleration/deceleration introduce errors. Since speed and length is required to evaluate the speed correctly and to compute accurate I-unit values, this has to be taken care of. One way to overcome this problem is to use a laser Doppler. In Figure 9 a laser Doppler has been integrated into a flatness gauge, giving accurate speed information but also plate length data with an accuracy better than 0.05 %. Length data and Doppler status information can be visualized in the user interface of the flatness gauge.
There are many more demands and requirements on a gauge that need to be considered, but beyond the scope of this paper for instance measurement accuracy requirements, stability and requirements on performance tests. These are described by Kierkegaard.[2] An excellent survey of how to define requirements on capability is documented by Q-DAS.[6]

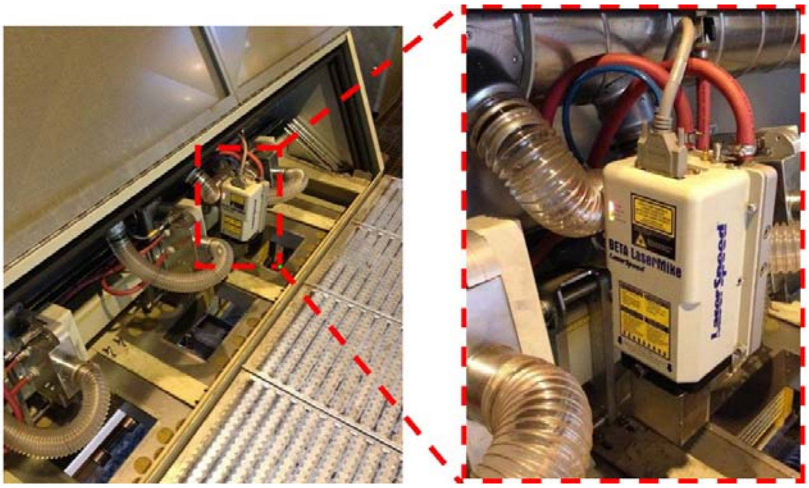


Figure 9. Integration of a laser Doppler. The water cooling and air-purge system from the flatness gauge has been used also for the laser Doppler, eliminating the requirement for high-pressure air and separate water cooling.

3.3 User Interfaces and Output Data

Presentation and output of data is of essence in order to utilize the gauge optimally. It must support accurate evaluation for decision making, continuous (streaming) data for control and output key-values for statistical purposes. Another important task is to provide graphs and data for efficient communication with steel users to improve customer support, update the flatness evaluation rules and adapt the product to current and future market needs.
Shapeline user interface has been developed based on customer requirements and interviews since more than 15 years. The latest version, Shapesoft 3, is modern, multi-functional and flexible software intended specifically for flatness measurement of flat metal products. There are tools for rapid automatic or manual decisions (Figure 10 and Figure 11), evaluations on individual (product ID) level, streaming data output for automatic control, configurable viewer software for on-line or off-line purposes, database functions, data export functions, automatic back-up functions etc. Specifically, the user interfaces and communication must be configurable and adaptable to the purpose it is intended for. Different applications have different requirements.

4 BENEFITS FROM FLATNESS MEASUREMENT

If flatness can be measured accurately and reliably, the processes can be tuned and controlled. Without measurement, we are more or less blind. This is a motivation on its own, but we can also put figures on the benefits.

4.1 Return on Investment

In general, it is difficult to calculate the benefits in dollars since they are manifold and often complex. How do you put figures on quality certification, customer satisfaction and continuous improvement processes when these are intertwined with other factors? At all times however, it is important to make accurate and objective decisions. To illustrate this, consider the following examples (from real applications).

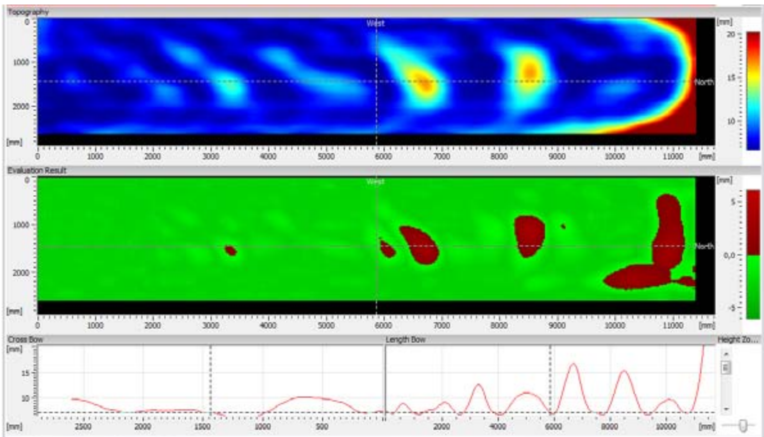


Figure 10. Part of the user interface. The top graph shows topography. The middle graph shows the result after flatness evaluation according to the EN10029-standard. Red color means areas out-of-specification. The bottom graphs show height profiles in the width and length directions, respectively for the positions of the dotted lines in the top graphs. Different parts of the maps can be viewed by just clicking a position in any the graphs.

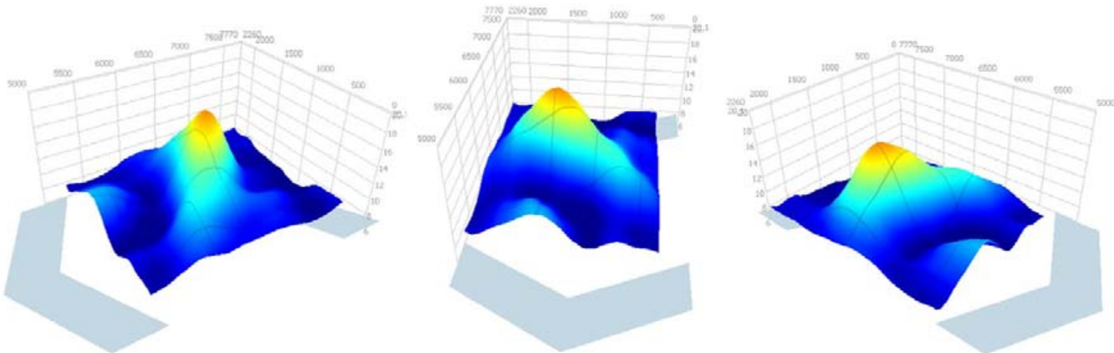


Figure 11. Part of the user interface. The figure shows a part of a plate zoomed in and visualized from different viewing positions. The light blue arrow indicates transport direction. Data can be viewed, scaled and zoomed in real-time. 3D views enable better understanding of the data but also help to make faster and more accurate decisions.

4.2 Plate Shearing Line

A plate producer has a shearing line which produces 250 000 metric tons per year. To be sure that the plates are flat enough, all plates are sent to a leveling line for flattening. The total cost for this is about 40 Euro/ton including storage and handling. In reality, nearly 50 % of the plates do not need leveling. The plates are already flat enough. By installing a flatness gauge in the shearing line 40*250 000*0.5 = 5 000 000 Euro can be saved per year. In addition, there are also other benefits such as the elimination of bottlenecks, quality assurance and feedback to upstream processing which in turn has potential for further significant cost savings.

4.3 Silicon Steel Line

An electrical steel producer trims strip edges to remove edge defects and edge waves. The edge waves are typically larger at the edge of the strip and decrease in amplitude towards the strip center (See Figure 12).

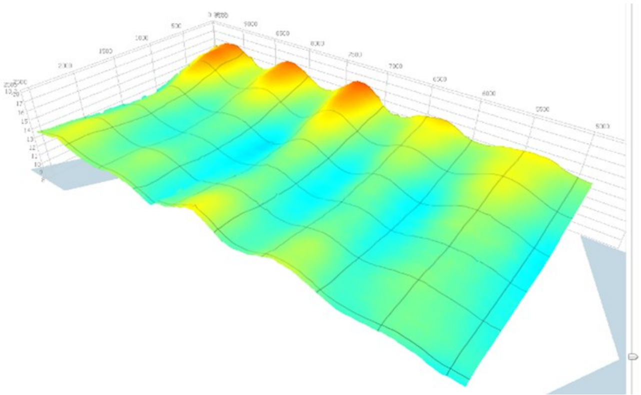


Figure 12. Edge-waves. The amplitude peaks at the edge and decreases towards the strip center.

At some position in width direction, the amplitude is lower than the threshold and the strip is useful. Hence, the edge-trimming position becomes crucial.
In economic terms, consider a line for oriented silicon steel. The price per ton is around 2 200 Euro. For the steel producer, the difference between prime material and scrap might be 1 500 Euro/ton. If 25 mm out of a 1 m strip can be saved, the earning is 2.5 %. In a line producing 100 k ton per annum this means 3.75 million Euros annually. For non-oriented silicon steel the benefit is lower due to a lower product price, but still significant.
There are many other examples such as improvement and tuning of leveling [6], protection of electrodes in EGL-lines, control of tension levelers for crossbow elimination, control of hardening processes for special steel and tuning of quenching for plates and strips (CAL-lines).

4.4 Demands from Steel Users

Another question is how flatness affects the end-users of flat steel products. To find out, Shapeline has carried out a study whereby 49 European steel users were contacted and most of them visited.(8) The companies all use steel sheets and plates to a significant extent.
The main problems related to bad flatness, as reported by the steel users, were:

- Laser cutting: feeding problems and damaged cutting heads
- Punching: feeding problems and material not released from the punching tool inside the machine
- Arc-welding: increased welding material and welding time

Specifically, for welding, the costs for bad flatness can be quantified. Every extra mm means increased welding time and welding material. In general, every extra mm results in more than 50 % extra production costs. This is why users of thicker material (which cannot be pressed flat) need to heat-treat the material to make it flat enough.
For instance:
: "*All plates with a welding gap larger than 1 mm are heat treated.*" Ruukki Constructions, Finland (manufacture structures for infrastructure e.g. bridges).
"Pre-treatment for better flatness is a large part of the final product cost and is included in the calculation." STX Europe, (shipbuilding)
"We need 2-3 % of our working time to handle flatness problems." Revent, Sweden (baking ovens)
When asked if the users are prepared to pay more for better flatness, over 50 % said "yes" or "partly". The accepted price increase varied between 4 % and 17 % with an average of about 10 %.

Worth noting are also the following comments:

- The standard flatness tolerances are too wide. Therefore, the users select suppliers based on the actual flatness and flatness guarantees.
- Mostly, there is no time for complaints. The steel is needed in the production to avoid delay penalties which can be substantial, especially for suppliers to the automotive industry.
- The users are small compared to the steel producers and often buy via traders or steel service centers. Due to this, information is lost and complaining is meaningless.

It is very clear that the requirements are different depending on how the steel is used. This is also stressed by some steel producers, e.g. from the AK-Steel homepage: "*The producer should determine the flatness requirements for its particular application and the suitability of this electrical steel.*" Also SSAB Sweden has a constant dialogue with their customers regarding flatness. "*There is a big difference in customer (flatness) demands,*" says Peter Ekholm, Project Manager at SSAB new cut-to-length line in Borlänge. This shows that the demand on a flatness gauge is not constant, but changes over time.

5 DISCUSSION

When deciding on the installation and implementation of a new flatness gauge, there are some important factors to consider. Firstly, the demands have to be clarified based on the use of the flatness measurement function, now and in the future. For quality assurance and evaluation according to international standards, a point resolution of 10-25 mm is required in both length and width directions. Lower resolutions may be used for internal and very thick plates, but there will always be a risk that the resolution is insufficient for material edges or future needs.

International standards also require a measurement accuracy of approx. 0.1-0.2 mm. This requires a measurement independent on surface variations as well as ambient light. However, no system will be independent on material transport and this factor is normally the limiting factor, not the measurement system performance itself. Consequently, the performance should always be tested under dynamic (hot) conditions. This means normal production speed, material and temperature.

An important factor is system calibration which can be done in several ways. However, of equal importance is the above mentioned line preparations and continuous system status check. The reliability of the measurement should be known for every plate or strip. Calibration may be performed as seldom as once per year, but in a steel/metal production line a lot can happen in one years' time. A Shapeline system can therefore check laser line alignment and reference points to check itself continuously. If the references are out-of-tolerance, the systems gives an alarm and should be calibrated and possibly adjusted.

6 CONCLUSIONS

We have proposed a concept for flatness measurement of flat steel and metal products, designed for real production conditions. In the paper we have described and exemplified the robustness and flexibility of laser line triangulation and how it can be realized in steel producing lines.

We stressed the importance of line preparations, such as the quality and configuration of the material transportation and correct speed measurement as well as the presentation and distribution of relevant data to various users.
In addition, we have showed the necessity of flat steel and metal to steel users and payback calculations showing short return on investment times.
Optical flatness measurement is a matured technology today and shows great benefits for quality steel and metal products.

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