

# High-speed archiving of thickness and profile data in the hot strip mill

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## Keywords

Hot strip thickness, data archiving, flatness, steel shape, x-ray profile gauge, profile control

## Abstract

Consumers of flat sheet steel demand the highest quality from their suppliers. If there are any questions regarding the final quality of the supplied product, modern data archiving allows producers to review recorded process parameters starting from its origins in the liquid phase to its final pass on in the cold mill. Any dimensional abnormalities can be traced upstream in the rolling process ultimately to the hot strip mill. The hot strip steel mill is universally considered one of the harshest environments for process instrumentation and sensors. While it is the ideal location to make critical dimensional measurements, the high temperatures that allow the steel to be more easily rolled to the required dimensions and the large volumes of water that control the cooling rates to achieve the required mechanical properties create significant design challenges for instrument suppliers.

This paper will describe a stereoscopic x-ray profile gauge with the ability to determine both the cross-thickness profile and the physical position of the strip in space. By using a narrow x-ray fan beam to measure the strip, the system can record the height of each point of the strip in the time domain. The flatness, or shape, of the strip can also be calculated. Recording these values in real time presents unique challenges to the data archiving hardware and software. Millions of data points can be recorded for each strip produced. Cataloguing terabytes of data for easy retrieval and analysis requires an application that is both robust and user-friendly.

The paper will review the architecture of several different data handling options and provide examples of visualizing the data through iba-Analyzer tools.

## Introduction

The versatility and strength of steel has resulted in its use in a wide variety of applications throughout the manufacturing world. In 2014, over 1.6 billion tons of crude steel were produced<sup>1</sup> and steel producers were challenged to differentiate their products in a market where conditions are less than ideal. World-class companies analyze volumes of data from a number of process variables to optimize mill operations for consistent and efficient production of high quality steel products.

## Process variables in the hot strip mill

There are many derivatives of the modern hot strip mill<sup>2</sup>, from multi-stand to reversing Steckel mills to direct casting, but the end goal is to produce a coil with uniform mechanical and dimensional properties from head-to-tail and edge-to-edge. Advanced process control algorithms use hundreds of variables from various sensors and drives to maximize the prime quality yield from each ton rolled.

Starting with the mechanical properties of the steel grade, strip tensions and temperatures are measured between every stand, pressure transducers measure reduction force and laser based velocimeters provide line speeds that monitor mass flow for use in feed-back and feed-forward control loops.

At the end of the mill, prior to strip coiler, a state-of-the-art, simultaneous profile gauge is used to validate the strip produced meets the tight dimensional tolerances demanded in the market place.

While each sensor contributes to the overall strip quality, the operator and mill computer are responsible for digesting those inputs and producing the desired product. The profile gauge has the ultimate responsibility for validating the specifications are achieved. In the past, if coil quality was questioned, the chart recording of the gauge output might be the only archived data to review. However, today, with high-speed data archiving, all of the previously mentioned variables and measurements can be recorded and reviewed by quality assurance, process engineers and plant management. Each discipline is able to mine the data for information critical to their areas of responsibility.

### Simultaneous Profile Gauge (SIPRO)

In the last two decades, the evolution and miniaturization of the integrated circuit has made high-speed radiation sensor arrays compact enough to fit into a robust frame for use in a hot strip mill. In the past larger ion chamber or scintillator/Photo-multiplier based detectors only provided a single measurement point averaged over several hundred square millimeters. The modern detector arrays can provide over 500 independent measurements providing a quantum leap in the percentage of strip area measured.

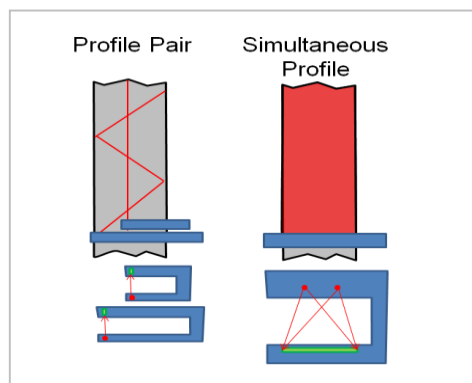


Figure 1. Measurement data from two single point style x-ray thickness gauges arranged in a profile pair compared to Thermo Scientific™ SIPRO

When these detectors are positioned below two x-ray sources arranged in such a way to provide a stereoscopic view of the full strip width, the Thermo Scientific™ SIPRO gauge is capable of providing not just a high resolution thickness profile, but a flatness value as well.<sup>3</sup>

The individual detector pixels are positioned every 6 mm across the lower arm of the stainless steel C-frame. When translated up to the level of the roller table, the resulting measurements are provided at a resolution of 5 mm of strip width. This high resolution provides mill operators information on ridges and grooves that are missed with lower resolution sensors.

The two x-ray sources of the SIPRO are positioned above the strip and arranged to view the strip from different angles. A unique rotating shutter design exposes the hot strip to one source at a time. Data from the detector array is collected every 5 milliseconds and is synchronized with the rotation of the shutter. At a strip speed of 15 m/s, this 5-millisecond update equates to a measurement value every 75 mm of strip length. Profile systems based on scanning or oscillating sensors require much more time and are 200 to 2000 times slower.

The positioning and synchronized data collection from the different sources also provides information on the physical position of the strip in space. In the event the strip is bouncing above the roll table surface, the profile thickness, width and all other measurements are not degraded.

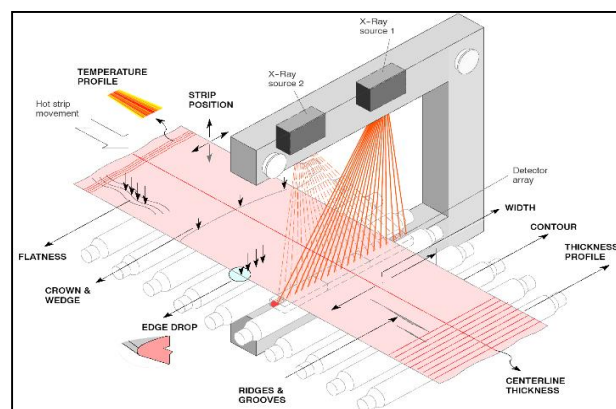


Figure 2. Dimensional measurements available from the stereoscopic SIPRO gauge

### Flatness measurement

The measurement of flatness is essentially a two-stage process. First, the contour is measured. Then, a history of the contour in the process direction is built up and the flatness calculated.

The contour calculation itself follows a number of stages:

1. Select a series of points across the strip - for which it is necessary to "locate" the strip.
2. Calculate the transverse gradient at these points
3. Integrate the gradient to give a relative height profile (contour)
4. If necessary carry out further iterations

The flatness calculation stages include:

1. Collect the height data along a set of “threads”
2. For each thread, calculate the length of the thread and the horizontal distance between ends.
3. Calculate the flatness.

### Locating the strip

The locations of the edges of the strip are calculated from the stereo thickness view - both the horizontal and vertical positions are known very accurately (See Figure 3). At this stage, because of the assumption that the strip has out-of-flatness, the vertical positions of points on the strip between the edges are not known. Initially however, the vertical position of each point on the strip can be estimated from the “trendline” - an imaginary line between the edges of the strip.

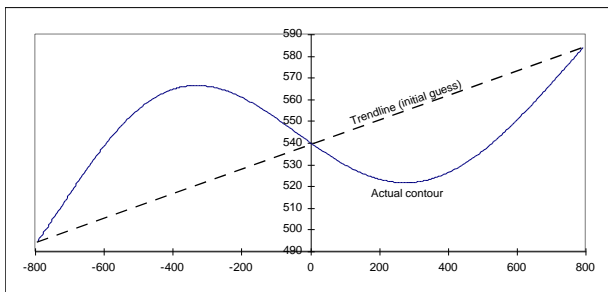


Figure 3. Contour measurement with trendline overlaid

It is possible to make a calculation of the contour using these points. If the thickness of a point on the strip is measured from two directions, there will be a difference in measured thickness, which is dependent upon the gradient of the strip. The gradient can be calculated from the two thickness values as shown in Figure 4.  $R_1$  is the resultant of the vectors  $t_1$  and  $t_2$  and its direction is the gradient of the strip. The directions of  $t_1$  and  $t_2$  are calculated from the positions of the detectors at which they are measured relative to the sources. These directions are fixed from the outset, since there is no movement of either source or detectors.

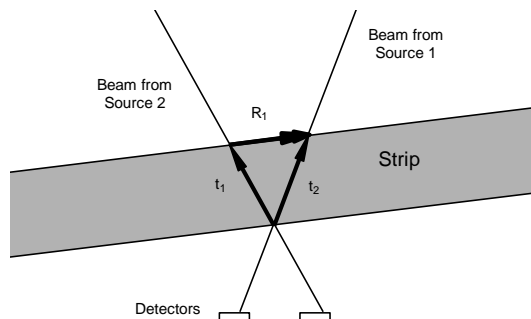


Figure 4. Calculating the gradient from a stereo thickness view of the strip. The view is along the process direction.

This method of measurement assumes that both surfaces of the strip are parallel - i.e. the thickness is not changing. Additionally, it assumes that the gradient of the strip is not changing. In both cases, the distance between detector elements becomes very important. When detector elements are 25 mm or further apart, there will be an error in the gradient. Therefore, it is essential that the transverse measurement resolution is as small as possible, so that the effects of changes in either thickness or gradient are minimized.

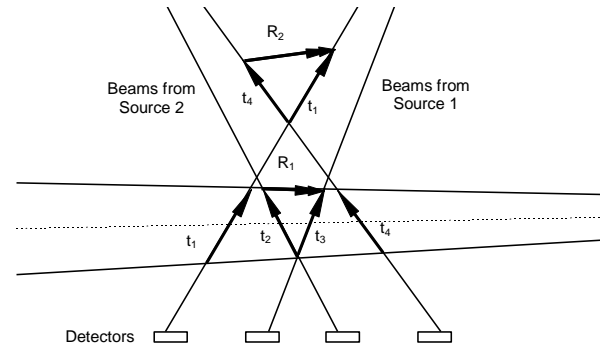


Figure 5. Potential errors when calculating gradient from stereo thickness measurements.  $R_1$  is in error because the thickness is changing.  $R_2$  is in error because the two views do not intersect at the strip.

Therefore, detector elements with a high cross-strip resolution ensure that the effects of changing thickness and gradient are insignificant, and allow the strip to be located in space very precisely. It is therefore possible to evaluate the height (and hence flatness) at any point across the strip. The true strip end-points are calculated from the stereoscopic views, and the contour is calculated from one end of the strip to the other. This allows us to relate the data to any point on the strip (for example, the center). Although the contour data is primarily a step in the flatness calculation, it can potentially be used to detect non-flatness features, such as tunneling.

The operator will want to examine the flatness at a number of predetermined points across the strip. These points extend in the process direction along ribbons or threads. The positions of the threads can be configurable and each time the contour is evaluated, the heights are calculated for each of them. For each thread, the height data is built up over time and can be related to the longitudinal position on the strip. The latter is calculated from the velocity of the strip and the time since the head of the strip was detected.

The flatness along each thread can be calculated in two ways:

- 1) Calculate the actual longitudinal length of the strip along the thread. This is the length of the thread if it was cut out along the length of the strip and allowed to lay flat

$$I = \left( \frac{\Delta L}{L} \right) \times 10^5 = \left( \frac{S}{L} - 1 \right) \times 10^5 \quad \text{Equation 1}$$

- 2) Calculate the amplitude and wavelength of a "wave" in the strip.

$$I = \left( \frac{\pi \cdot a}{\lambda} \right)^2 \times 10^5 \quad \text{Equation 2}$$

In the second method, the amplitude and wavelength can be calculated using fourier analysis. Fourier transforms are good at filtering out unwanted noise and non-cyclic changes. The discrete fourier transform has drawbacks however. It can only detect discrete wavelengths, leading to resolution problems. If there is more than one component in the wave, the analysis can be difficult. There is an upper limit to the wavelengths that can be detected, dependent upon the number of measurements that are taken (and hence the time spent taking them). Finally, a relatively large number of points are required for an effective analysis, leading to a long delay before results are given.

The first method involves calculating length differential directly. This avoids many of the problems associated with the fourier method. However, there are still challenges. There is the possibility of noise in the height measurement, partly due to thickness noise and partly due to non-out-of-flatness related height variation. Appropriate smoothing is required to avoid any erroneous out-of-flatness (noise in the height data would always involve an increase in the flatness measurement). There are a number of methods, which may be suitable for this kind of smoothing, and these are under investigation.

### Data archiving architecture

As mentioned previously, the SIPRO system is collecting and calculating hundreds of measurement values every 5 milliseconds. Over the short 45 to 90 seconds timeframe required to roll a single hot strip, over 1 million analog data points can be collected including:

- Thickness measured from source A
- Thickness measured from source B

- Temperature measured from Scanning Pyrometer
- Width
- Crown and Wedge
- Flatness
- Location of any grooves or ridges

Additionally, the system diagnostics monitors dozens of internal analog and digital sensors related to gauge operation, interface commands and overall health.

This volume of data creates storage challenges for over 25 MB of disk space required per coil. The first and easiest approach is to select on those key parameters to record and set the system to record a filtered signal that averages over a longer timeframe. However, when smaller defects occur at high speed, the high-resolution data storage is needed to analyze the abnormalities.

There are three common hardware arrangements to consider or data storage on the SIPRO system.

- 1) The first is to store the data files directly on the gauge computer.

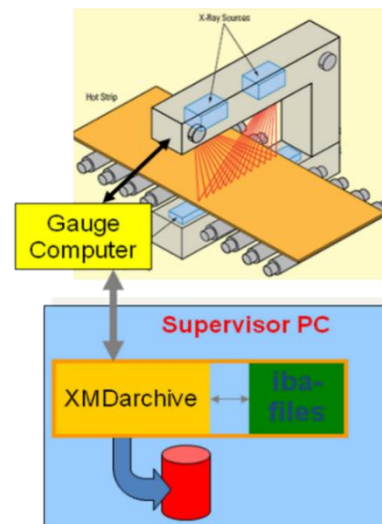


Figure 6: Data archiving using gauge computer

This arrangement is compact, but limits access and review of data unless it is transferred on a regular basis to a server or other storage location.

The gauge computer converts the data collected directly to an iba .dat file for easy display through the iba PDA software. In order to have manageable file sizes, the profile data is archived every 200 ms.

- 2) The second method of data archiving transfers the data from the Supervisor PC to a dedicated ibaRackline Archiving PC with ibaPDA V6-2048 module. Data transfer is handled via traditional



TCP/IP, which has the benefit of widespread use in other applications, and off-the-shelf hardware availability. Additionally, the archiving PC can be physically located further away from the harsh mill environment and connected to a mill wide server for regular back up and storage. Profile data, along with temperature and shape information can be stored at intervals of 200 ms, with 10 ms rates for key parameters such as centerline thickness. The one limitation is that only 4096 bytes are allowed per interface.

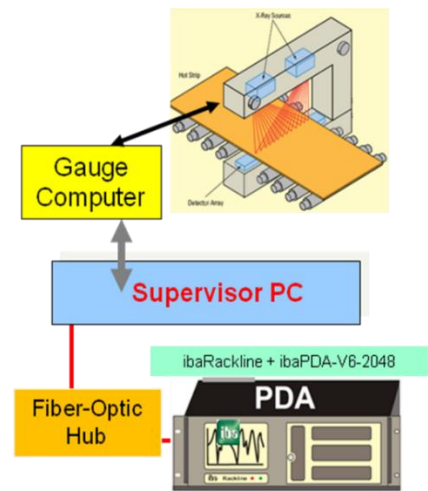


Figure 7. Data archiving using Ethernet link to ibaPDA Archiving computer

- 3) The third arrangement for data storage uses reflective memory (RFM) between the Supervisor PC and Archiving PC. This configuration requires the use of a fiber-optic connection in place of the Ethernet link.

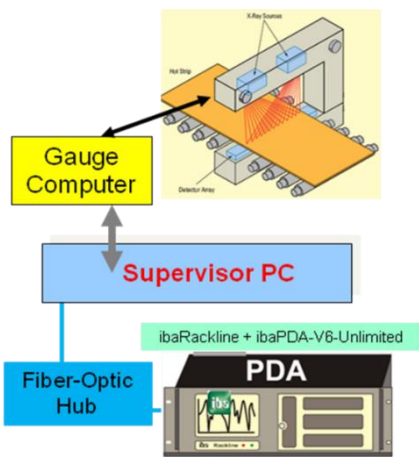


Figure 8. Data archiving using Fiber-optic link to ibaPDA Archiving computer

The RFM arrangement allows for high-speed data storage. Specialized hardware components are required for this architecture. The GE PCIE-556RC provides the reflective memory interface between the gauge and storage computer. An iba storage computer needs to be licensed for an unlimited number of variables. All profile data and key parameters can be sent at a rate of 40 ms and the flatness and diagnostic data can be recorded every 100 ms. The diagnostic data allows process engineers to view individual source views to verify the location of any defects in space.

Regardless of the data archiving arrangement, profile data can be stored on a coil-by-coil, shift-by-shift, or daily basis.

The reflective memory arrangement can also be used to integrate the gauge data into the mill’s own process control archiving. This allows gauge parameters to be charted alongside mill control parameters.

### Coil reports and analysis of archived data

Using the flexible tools of the iba Analyzer software, process and quality engineers can create PDO templates and import data from any stored file. Data files can be converted to coil reports with statistical data and quality information. Two- and three-dimensional profiles can be viewed and analyzed for variations, and dimensions that are out of specification. The zoom feature can help determine exact locations of defects in the strip and the ability to compare multiple coils can reveal system wide maintenance needs.

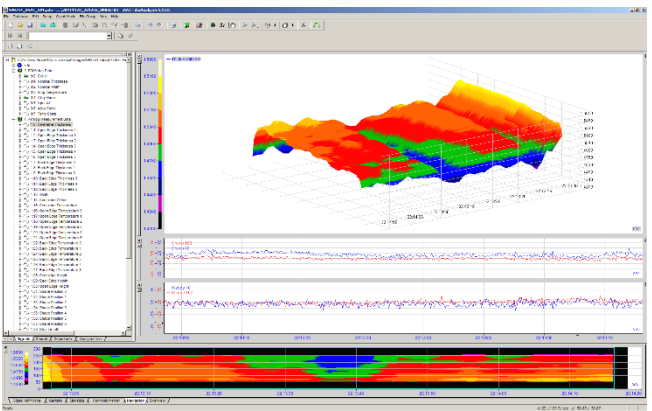


Figure 9. iba analyzer software display of 3-D profile data from SIPRO

Future developments of very high speed analysis of the individual source views at a rate of 5ms for a full profile has proven extremely promising for identifying small defects in the hot mill that can result in major quality concerns downstream.

Currently, high volume storage of data at this 5 ms rate is only possible with internal storage of .dat files that can be evaluated post production. In Figure 10, a void in the steel of approximately 40 mm in diameter was captured in the profile data. The strip speed was approximately 10 m/s so the defect was only measured by the gauge for 15 ms. The void resulted in an increase in the x-ray signal and thanks to the stereoscopic view of the SIPRO, its position within the strip was identified. The defect was addressed before the coil was processed any further, thus saving the producer's reputation as well as lost production time in the cold mill.



Figure 10. Photo of 40 mm void detected by SIPRO in hot strip mill running at 10 m/s

## Conclusion

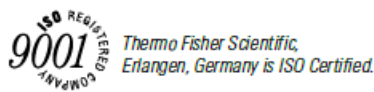
The quality of the steel produced in the modern hot strip mill has a direct impact on the success of steel producer's business. A high-speed simultaneous profile gauge is an essential component of the mill that provides not only critical dimensional information in real time for profile and shape control, but also the ability to identify defects before they impact the downstream processes. The archiving of millions of process data points from the profile gauge requires aligning the data handling hardware with the needs and expectations of the process and quality engineers. When properly configured, the profile archiving system becomes an invaluable tool to maintaining dimensional quality in the hot strip mill.

## Acknowledgments

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