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A multi-function measure system for hot-strip mills

A radiometric system based upon the 'stereoscopic' principle has been developed, providing accurate and reliable measurement of the many parameters relating to product gauging, which are required to control, monitor and evaluate a modern hot-strip mill.

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Due to unique sensor design features and multiprocessing real time computer systems this radiometric system gives measurements of strip thickness, thickness profile, temperature profile, width, strip position, speed, camber and flatness, with accuracy and response times equivalent to those of industry-standard dedicated instruments. All that is required on the line is a single C-frame housing all the sensor elements.

As befits a multifunction gauge, extreme robustness, accessibility, system redundancy and rapid online fault diagnosis - which can be remotely accessible – ensure minimum downtime.

System architecture

The sensor consists of a cooled stainless steel C-frame (see Figure 1), housing two high power x-ray sources in the top arm and a continuous array of radiation detectors in the bottom arm. A scanning pyrometer is fitted as standard, and a laser velocity gauge may be fitted as an option. The C-frame does not move during normal operation, but can be driven offline for maintenance.

The two radiation sources alternately illuminate the entire strip width with 5 ms (millisecond) exposures. This is achieved by using rotating tungsten shutters which are coupled together in anti-phase.

The purpose-designed radiation detectors are assembled in 32-channel modules. The detector elements form a continuous array of high-efficiency scintillators and custom photodiodes on a 6 mm pitch. Each module has its own electronics package, including a 20-bit analog-to-digital converter for each detector. This ensures that the sensitive analogue signals generated by each detector element are unaffected by the high electrical noise levels normally found in hot-rolling mills

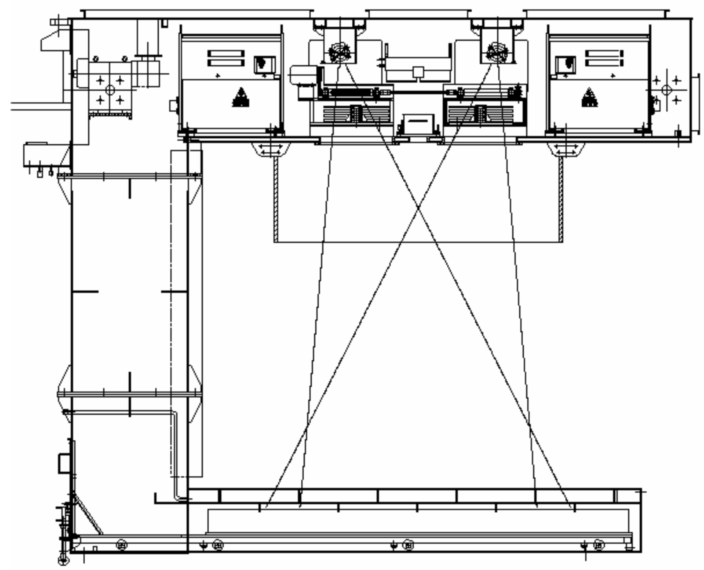

Figure 1 **C-Frame and sensor arrangement**

A typical system has 16 contiguous modules, giving a linear array of 512 detectors with no gaps (see Figure 2). The signals from each 5 ms exposure are digitized within each module and sequentially transmitted to a multi-processor VME computer system via a high-speed synchronous serial link.

Thickness and profile measurement

For every 5 ms exposure, the computer calculates an apparent thickness for each detector giving a raw thickness profile. It then analyzes the results of the current and previous scans to locate the edges of the strip in space (see Figure 3).

The thickness profile is then calculated by working along a straight line between the two edge positions. For every 5 mm of strip width, the measurements from the two source views are combined, taking into account the known strip angle, to give a strip thickness profile measurement insensitive to position or tilt.

The first requirement for a hot-strip mill gauging system is to provide a fast low-noise centerline thickness output for automatic gauge

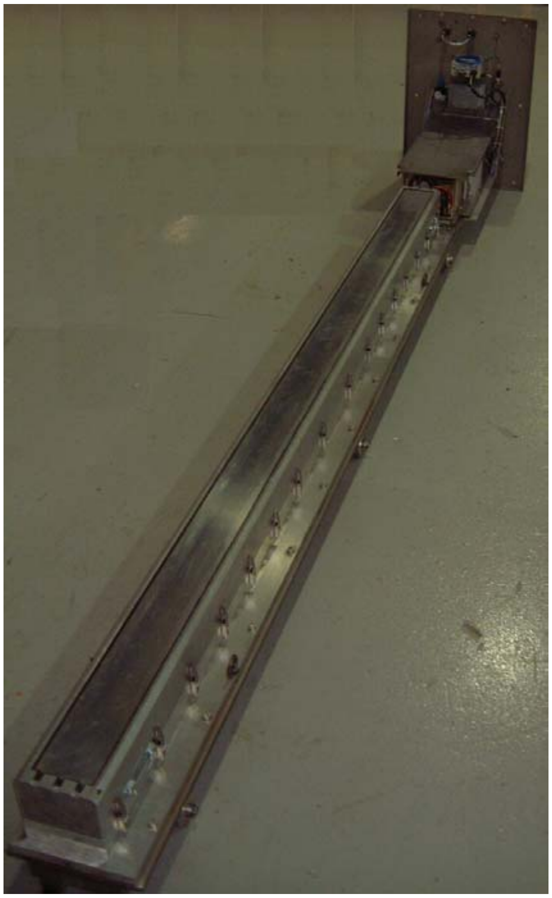

Figure 2 **Linear detector array**

control (AGC) purposes. This is achieved by averaging each 5 ms profile across a section of the center portion, 100 mm typically being used. A running average is made of the last three samples before making the output. This gives better than 0.2 percent thickness noise, with the digital equivalent of an analogue 10 ms response time. If a longer or shorter response time is required, this can be adjusted by the user.

Some control systems also require real-time crown and wedge outputs. The system provides these by further analysis of each 5 ms thickness profile, this time using much smaller sections of profile width. Normally, a slower response time is required and the crown and wedge values are passed through a longer running average before output. Again, this is user adjustable, but is typically set to 200 ms. It is important to realize that it is the results from each 5 ms profile that are averaged, instead of averaging the profile and then making the calculation. This gives a continuous real-time output.

Width and position measurement

As a consequence of the above calculations from each 5 ms exposure the, current strip-

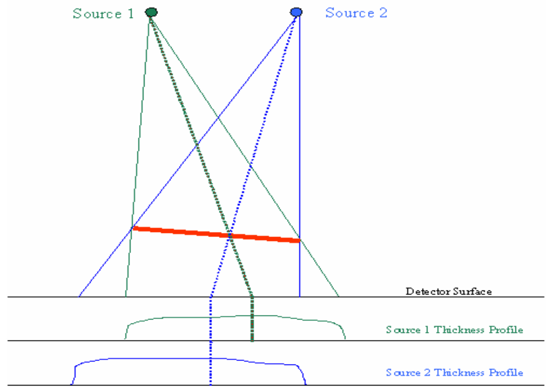

Figure 3 **Thickness and profile measurement**

edge positions are known to better than 1 mm resolution. The high resolution is achieved by interpolating the last detector at each edge, and so makes it straightforward to give a strip width, position and height measurement as good as a conventional stereoscopic optical gauge. As with the other measurements, the values are passed through a user-adjustable running average before output, remembering that it is the calculated 5 ms results which are averaged, not the edge positions. Thus the width output is unaffected by position or tilt, and the width measurement is available even from the very head of the strip when it is unconstrained by coiling tension.

Temperature measurement

The real-time analogue output from the scanning pyrometer is directly digitized by the gauge computer. The pyrometer makes 25 scans per second, so a new temperature profile is available every 40 ms. From this, a strip temperature profile is built with the same 5 mm cross-width resolution as the thickness profile. For each 5 mm across the strip, thickness measurements are individually temperature-corrected using the local strip temperature.

Real-time analogue outputs of temperature at selected positions across the strip width are available if required.

Cross camber or contour measurement

Cross camber is defined as the variation in the height of the strip across its width, often associated with out of flatness. It is not normally a measurement required in its own right, but it is an important stage in making a flatness measurement. It is also used for correcting the width and thickness measurements that can be affected by strip which is not flat (see Figure 4).

The first stage in measuring cross camber is to calculate the strip gradient by analyzing the two source views. If the strip is tilted, it will look thinner from one source and thicker from

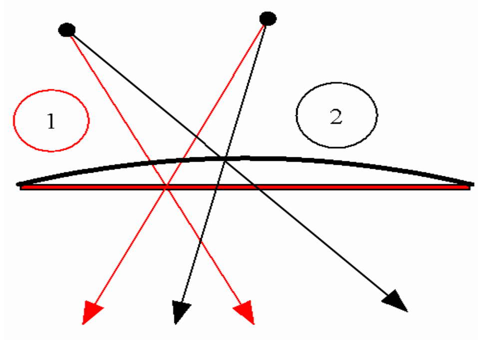

Figure 4 Camber measurement

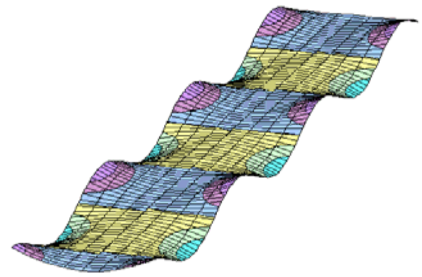

Figure 5 Flatness measurement threads

the other. The gradient can be calculated from the difference. By working along an assumed straight line between the edges, a polynomial function for the gradient is derived. This function is then integrated to give a new polynomial function that approximately describes the strip height. The known edge positions provide the constant of integration.

A second iteration of the above calculation follows the newly calculated approximate height function between the edges instead of the previously assumed straight line and significantly improves accuracy.

The thickness measurements are then corrected for the newly calculated strip angle, and a more accurate width is calculated from the actual length of the polynomial function between the edges.

All these calculations are done every 5 ms using a fast floating-point DSP processor. Real-time analogue outputs of height at selected positions across the strip width are available if required.

Flatness measurement

Flatness is measured by tracking height variations with length. Height samples are stored every 10 ms for a thread on every 50 mm of strip width (see Figure 5). The strip travel length for each set of samples is calculated from a strip speed signal. The speed signal can come either from an incorporated laser speed gauge or from an external source

To calculate flatness for each thread, the height variations over a configurable length of preceding strip travel distance are analyzed to yield an actual strip length. Flatness in I-Units is calculated in the standard way, as the ratio between the actual strip extension length and the strip travel length. The cross flatness information is then analyzed to yield symmetric and asymmetric flatness measurements.

All the results are recalculated every 10 ms for every thread using a separate DSP processor, and real-time analogue outputs are available of symmetric and asymmetric flatness or the actual thread flatness at selected positions across the strip width.

System outputs

As described above, the system can have up to 18 analogue outputs for measured parameters such as centerline and edge thicknesses, crown/wedge, width, position, centerline and edge heights and flatness for selected threads. These are typically used for Level 1 control systems.

For higher level data-processing, display and archiving systems, all the information is available digitally. Successive 5 ms strip profiles are averaged, and, typically a complete strip thickness and temperature profile at 5 mm cross-strip resolution is available every second. Averaging is done using the strip-based co-ordinate system, and so gives a true strip average unaffected by position or tilt.

Thickness profiles can be further analyzed for numerical crown, wedge, edge drop values and to detect ridges and grooves as small as 10 microns high and 10 mm wide,

A network telegram is typically sent every second containing all measured information including thickness and temperature profile at 5 mm resolution and flatness for each 50 mm spaced thread.

A strip summary feature is also optionally available, whereby all the data for each strip is accumulated and processed at the end of its measurement to generate statistical information. This gives separate average data for the head, body, tail and total strip length. Tail and head length are user-configurable or can be set on a coil-by-coil basis. The data includes thickness profiles for each region together with minimum, maximum, mean and sigma values for thickness, width, temperature, crown, wedge, position and flatness.

System displays and archiving

The Windows-based system display unit has a process page giving an overview of all measured parameters. This includes thickness and temperature profiles together with real-time traces of thickness, temperature, width, crown, wedge, symmetric and asymmetric flatness along the length of the strip. Current measurement values are shown digitally.

The optional data-archiving station stores measured data in an SQL archive. The system is totally configurable and the user can choose to archive any measurement on a timed or event-driven basis. The former would normally be used for logging measured thickness, width and so on along the length of the strip, while the latter enables strip summary data to be archived at the end of its measurement.

An evaluation tool allows very flexible searching of the archive. For instance it can be done on a time/date basis, a product parameter basis such as coil identification, target thickness, alloy grade and so on, and also on a measurement data basis such as crown above or below a certain value. Of course logical combinations of any of these are also supported.

Robustness, reliability and redundancy

The system is designed for continuous operation in the harsh environment of a hot-strip rolling mill. The C-frame is 10 mm thick stainless steel with internal water-cooled heat shields. Hatches on gas struts allow easy access to all top arm parts, while the entire detector module can be easily withdrawn from the rear. Any major component such as an x-ray tube or a detector module can be replaced within 15 minutes.

Metal ceramic x-ray tubes are used operated well below their maximum rating. The system can still operate for AGC, profile and width measurement with only a single x-ray source by assuming the strip is flat on pass line. Faulty detectors are automatically discovered and excluded, while the appropriate warning is flagged.

Diagnostics

The system has extensive diagnostics, all of which can be accessed remotely via dial up modem or internet if the customer's firewall permits.

All digital and analog I/O values may be exercised and monitored via a built-in maintenance screen. Alarms are generated for inputs going out of preset bounds or in an unexpected state. Separate screen pages allow monitoring of the x-ray sources, pyrometer and detector array. Network and serial data links can be monitored and traffic logged for analysis.

Internal reference plates are measured during the system's initial calibration against certified external samples and thereafter may be checked automatically, allowing the gauge to compensate for any drift or change. Both calibration and check data can be imported into Excel, allowing for quick identification of any faults. Additionally, a full measurement diagnostic facility allows on line logging of all the signals, intermediate calculation stages and final measurement results.

Online results

The system has now been installed on hot-strip mills throughout the world. The first systems provided thickness profile and temperature measurements, then the width was added and later the flatness function. Enhancements of the data-processing and output capabilities have been continuous. The measurements have been validated online at each development stage. On older mills, the primary reason for installing the gauge was the acquisition of thickness profile measurements, the system's additional measurements being used as backups for existing sensors. However, on newer mills, it may be the only strip gauging sensor required. In either case, the system provides unprecedented levels of hot-strip measurement and characterization.

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