Measuring technology and quality assurance in packaging steel production

J Schwarzmann
Development Department for Gauging Technology, IMS Messsysteme GmbH, 42579 Heiligenhaus, Germany

Abstract. Tinplate, being used primarily for packaging purposes, went through a considerable development over the last decades. Its quality was continuously improved enabling significant savings in material consumption and production economy and ecology. A premise for that progress is the development of advanced measurement and inspection equipment. It utilizes different physical principles to allow an online monitoring of important material parameters for regulation feedback or quality control. One of the latest developments is an online inspection system for non-metallic inclusions. It is based on magnetic flux leakage which is contactless detected by arrays of differential GMR sensors. The sensors are mounted to compact sensor modules containing all required peripheral equipment. Multiple sensor modules are connected to hubs which convert their data stream to the GigE camera standard. The resulting device resembles a magnetic line camera covering the whole surface of the inspected strip. The recorded images are processed by a software to detect and classify defects from the material noise.

1 Tinplate
The use of rolled iron or steel for packaging purposes ranges back to the early 19th century. Since, a typical form of packaging steel is tinplate: thin, rolled iron or steel plate with tin plating for the purpose of corrosion protection. Zinc plating has better anticorrosive properties and protects the substrate even in case of surface damage, unlike tin, by cathodic protection. However, zinc plating is not food safe and does not provide a decorative surface quality as tin plating. Hence tinplate has become an important material for food as well as high-grade decorative packaging applications.

Initially, tinplate was produced by hot rolling of bundles containing multiple plates. The tin layer was applied by putting the plates into baths containing molten tin (fire tinning). By the middle of the 20th century, the bundle rolling method for obtaining thin steel or iron plate was replaced by cold rolling, first on reversing and later on tandem rolling mills. Now cast steel slabs are hot rolled into plate with a thickness of 1,5 mm - 4 mm. After the removal of scale and rust by electrolytic pickling, the plate is cold-rolled to the final thickness, which is 100 µm - 500 µm. The rolling is followed by annealing and temper rolling to define the plates mechanical properties and surface texture. At the same time, the fire tinning process was replaced by electrolytic tin plating. This plating method produces a matte surface finish. The surface structure and thus the materials appearance can be modified by inductively heating the tin plated strip, liquefying the tin coating and thus creating a smooth, shiny surface. Depending on the application, it may be followed by a film or lacquer coating. All these production steps have gradually developed to continuous processes. The latest progress is the online laser-welding of the ends of individual strips enabling truly continuous production. 97% of the produced tinplate is processed for packaging applications. Typical products are decorative packaging, food, beverage and technical cans...
as well as lids and bottle caps. In that function, tinplate offers a number of advantages over other packaging materials. Steel packaging can be easily separated due to its ferromagnetic behavior and, due to its high strength, used at a very small thickness. It also can be recycled infinitely with nearly no loss of quality. The resulting recycling rate in Germany is over 90%. The reduction of material consumption per pack is another approach to enhance the economy and ecology of steel as a packaging material. It is made possible by the usage of specialized materials with precisely maintained properties and allowed an average reduction of material usage in packaging application of approximately 20% over the last three decades. For deep drawn beverage cans, the reduction by the course of 20 years even was 32%: While 1985 the weight of a 0.33 l cans body was 32 g, it could be reduced to 21.5 g in 2005.

The permanent improvement of tinplate quality as well as the ability to supply a high number of material grades with different properties, among others, became possible by the development of advanced measuring and inspection equipment.

2 Measuring and inspection equipment in tinplate production

A wide range of different measuring and inspection equipment using different physical principles is required for the production of tinplate meeting today’s quality demands.

2.1 Thickness measurement

The production of packaging with the smallest possible material input requires very tight tolerances in material thickness. Hot as well as cold rolling of steel plate to precise dimensions requires a fast and accurate online measurement of the materials thickness. Because of the high material velocity during rolling as well as the high temperatures during hot rolling and the delicate surface after cold rolling, a contactless thickness measurement is necessary. A possible solution is a measurement by laser triangulation: A laser projects a dot or a line onto the surface. The scattered and reflected light is observed by a detector at a defined angle. A change in the position of the surface causes a change in the position of the reflected light on the detector. The usage of two suchlike devices, placed on both sides of the strip at the same spot, with an accurate calibration allows a precise thickness measurement. While the utilised measuring principle is simple, it leads to a number of difficulties. The accuracy of the measurement depends on the mechanical stability of the measuring gauge. As typical strip widths are over 1000 mm, the construction of a gauge of such dimensions and a long-term stability in the micrometer region is challenging. The measurement requires some amount of light scattering on the materials surface. Thus, very shiny surfaces, as often found on rolled and especially plated metal, can cause insufficient or excessive illumination of the detector. The same applies for extraneous light, radiation of the hot strip during hot rolling and obstacles in the optical path, like steam, mist and heat haze.

As with any other measurement method, the measurement of material at an angle will lead to excessive thickness values. With the measuring principle described above, any misalignment of the upper and the lower measuring points will dramatically intensify that effect.

A different, technically very sophisticated, approach, is the radiometric thickness measurement. A highly stable radiation source and an also stable and sensitive detector are placed on different sides of the strip. The radiation is partially absorbed by the strip, dependent mainly on its thickness but also on its temperature and alloy. Mechanical inaccuracy of the gauge and slight obstacles in the beam path do not have a high impact on radiometric thickness measurement.

Initially, only encapsulated radionuclides were used as a radiation source. They offer the advantage of a very constant activity with a narrow energy band which simplifies the calculation of the materials thickness from the measured intensity. Their decay energy is chosen to be convenient for the measured materials thickness and density. The drawback of radionuclides as a radiation source is their limited service life (half-life usually in the years or decades region) and their permanent radiation. To get the ability to turn off the radiation, the capsules containing the radionuclides are mounted into tungsten blocks which can be mechanically shut.
With the availability of highly stable and durable x-ray sources as well as more performant computers, x-ray tubes replaced radionuclides as a radiation source in many radiometric thickness measurement applications. While offering the advantage of being easily turned off and having adjustable operating values, they have the drawback of emitting bremsstrahlung with a complex energy spectrum instead of nearly monochromatic radiation. That complicates the calculation of the materials thickness from the measured intensity as the absorption coefficient is energy- and alloy-dependent. However, the required calculations are easily handled by modern computers. The current measuring accuracy of radiometric gauges for thin steel plate is in the micrometer range.

Figure 1. Sketch of an x-ray thickness gauge.

Both types of radiometric gauges require regular calibration to compensate radiation source and detector drifts and obstacles in the beam path. For that purpose, they contain a set of accurate metal plates which are, for a calibration procedure, automatically pushed into the beam path in different combinations. Radiometric gauges with one or three stationary or traversing measuring points as well as profile gauges with a high number of detectors arranged in a line are available.

Optical as well as radiometric thickness gauges require temperature compensation, especially for hot rolling: The materials outer dimensions increase with rising temperature. On hot material optical thickness gauges will measure a higher thickness compared to cold material as it would also be the case for a simple mechanical measurement. On the contrary, the materials density decreases with temperature leading to lower thickness values measured by radiometric gauges.

2.2 Width measurement
The production or distribution of material with excessive width makes necessary edging and thus causes scrapping of unused material. Therefore, the production of strip with an accurate width leads to immediate material saving.

Width measurement is accomplished optically by measuring the shading of a light source or the projection of a laser line on the material. The first principle uses a fluorescent or LED light source providing an uniform lighting, which is placed under the measured material. For very thin material with a stable position, a single camera is placed above the strip, gauging both edges. The width of the material
can be calculated from the position of the materials shadow on the camera. For thicker material, the position of the shadow also depends on the material's thickness. In this case, a stereoscopic measurement, thus two shifted cameras, are necessary for an independent width measurement. Another option are traversing cameras which are automatically moved over the material edge, resulting in a true vertical measurement and thus eliminating the need for any thickness or position compensation. For complex edge geometries, which are often found on hot rolled material, or a wide range of material widths, a stereoscopic measurement of both edges (a total of 4 cameras) is applied.

The second principle uses a high number of small cameras aligned in a line over the material. Each camera only views a small section of the strip. A laser line is projected onto the material. Outside of the material's edges, there is no reflection of the line to be detected by the cameras. The length of the detected line allows a calculation of the material width. This measuring principle can only be applied on thin material.

2.3 Coating measurement

The enhancement of the quality of the tin plating and its passivation allowed a gradual reduction of the applied coating weights, which requires an examination of the latter.

Coating weights of metal plating can be measured radiometrically utilising the effect of x-ray fluorescence. A x-ray tube exposes the material's surface to radiation. Some of the photons interact with the substrate or the coating by ejecting electrons from the k-shell of their atoms. The missing k-shell electrons are replaced by l-shell electrons, which release their excessive energy by the emission of a photon. The energy of an incident photon must be higher than the binding energy of an k-shell electron to cause k-shell ionization. At the same time, the closer the energy of the incident photon is to the k-shell electrons binding energy, the higher the probability for the described interaction.

The acceleration voltage of the x-ray tube is adjusted for the radiation to be well-absorbed by the iron substrate but to pass the tin plating, which has a significantly higher k-shell binding energy.

The iron substrate fluoresces at an energy of approximately 6.4 keV, which is well absorbed by the tin coating. The backscattered fluorescence radiation of the iron substrate passing the tin coating is measured by multiple, very sensitive ionization chamber detectors placed around the x-ray tube. The reduction of the detected radiation intensity compared to an iron sample without a tin layer is used to calculate the tin plating thickness based on a calibration curve.

2.4 Flatness measurement

A strip is termed unflat if different longitudinal sections have different lengths. This causes the strip to bulge at regions with excessive length, resulting in an uneven appearance when laid on a flat table. The amount of excessive length can be approximately calculated from the height of the appearing waves and their density. The origin of unflatness are inaccuracies during the rolling process. It is undesirable as it can cause problems in automatic processing of the plate or with the quality of the finished products.

For strip with low or no tension, the flatness can be measured optically: Two laser lines are projected close to each other across the strip. They are monitored by a line of cameras, calculating their height by triangulation. A periodical height difference indicates bumps caused by unflatness.

That principle is not applicable for tensioned strip, as possible bumps caused by unflatness will be smoothed by elastic elongation. In this case, the strip is guided over a roll consisting of a thin shell over a number of pressure-sensitive elements arranged axially along the roll's axis. Unflat material will cause an uneven force distribution along the rolls surface which is detected by those elements.

2.5 Pinhole, edgecrack detection and surface inspection

Imperfections in the rolling process can result in small holes or in cracks at the edge of the material. While at least resulting in defective products during final processing, they can even cause a rupture of the strip under tension in a processing line due to the caused notch effect. Surface defects like scratches, dents or staining can impair the finished products.
Holes and cracks are detected by a line of cameras picking up light passing through the holes and cracks, provided by a strong light source placed under the material. Surface inspection is also performed by fast cameras observing the materials surface, identifying irregularities by a specialized software.

2.6 Oil film measurement

Tinplate is typically coated by a very thin oil film for lubrication and corrosion protection purposes during the subsequent processing. The application of additional layers like painting without further cleaning requires the oil film not to exceed a critical thickness. At the same time, a too thin or incomplete oil film can cause the plate to stick to itself or to processing tools.

A recently developed optical measuring system enables the online measurement of thin oil films with up to 30 nm thickness by ellipsometry: The material is illuminated at the Brewster angle of the metal substrate by linear polarized light from a laser source. The oil film as well as other translucent surface layers transfer the initially linear polarization of the light to elliptical polarization with its ellipticity being dependent on the layers thickness. By empirical calibration with known surface conditions and layer thicknesses a monitoring of the applied layer thickness is possible.

3 Internal defect detection

Tinplate can contain internal defects like pores and non-metallic inclusions (NMIs) which initially remained in the slab during casting at the very beginning of the plates production process. At the same time, a progressive saving on tinplate consumption for packaging purposes requires a high purity. The production of packing often involves processes subjecting the tinplate to high deformation ratios. In that applications, even small pores or inclusions of non-metallic materials inside the strip can cause holes in the finished product or material rupture during production. As that kind of defects are mostly hidden inside of the material, they cannot be detected by optical inspection. As an online measuring system would have to inspect material at speeds of up to 1000 m/min, a radiometric inspection, as widely applied in general NDT, is not feasible.

A common offline inspection method for NMIs in ferromagnetic material is magnetic powder testing, which is based on the effect of magnetic flux leakage: The inspected material is magnetized by an external magnetic field and sprayed by ferromagnetic particles. Non-ferromagnetic NMIs cause a local change in the material’s magnetic cross-section, inducing an inhomogeneity in its magnetic reluctance. This results in a variation of the magnetic field strength on the materials surface leading to an aggregation of that particles indicating a defect. The refraction of the magnetic field upon passing out of the materials surface, caused by the large permeability difference between the material and the surrounding air, enlarges the leakage field extension, which benefits the measurement [1].

![Figure 2. Sketch of the magnetic flux leakage of a surface crack in ferromagnetic material.](image)
While magnetic powder testing is a protracted process with limited sample size when conducted automatically, magnetic flux leakage can also be used for online NMI detection. The leakage field is detected by recently developed, compact sensor modules, containing an array of GMR sensors, amplification, signal filtering and digitalization as well as an electromagnet for magnetization and power supplies for the listed components.

Figure 3. CAD image of a sensor module without its outer housing.

The measurements on moving material required for the design of the sensor module were conducted on a test stand. It uses non-magnetic discs on which samples can be glued, containing natural or artificial defects. That defects can be reproducibly passed under a sensor, testing different sensor types and orientations, liftoffs and magnetization configurations. While the steel plate used for samples may have structural anisotropies caused by the rolling process, there was no observable effect on the material’s magnetic behavior by the change of the material's moving direction to its original rolling direction.

The used sensors are gradiometers with a sensitive area distance of 1 mm. They are arranged in three rows, resulting in a spatial resolution of 1 mm. A higher resolution would not be useful as the required smaller sensors are less sensitive due to their smaller active areas. At the same time the smallest defects detectable by amplitude induce a leakage flux with dimensions of around 1 mm.

Different magnetization directions were tested. A magnetization parallel to the material moving direction has several advantages for the construction of a measuring system. That configuration also gains a higher SNR for compact defects like round holes. A magnetization across the materials moving direction results in a lower SNR for compact and a higher SNR for elongated defects [2]. A 45 ° angle between the magnetization and the materials moving direction was found to reduce the amplitude of compact defect signals while providing no increase to the signals of elongated defects. The sensor modules were designed for a crosswise magnetization despite the constructional drawbacks, as most defects occurring in the measured material have elongated shapes due to rolling [3]. The electromagnet's current can be regulated by a buck converter to adapt its magnetomotive force to different measured materials.

The leakage field of small defects, although being extended by refraction, still has only small dimensions. It is thus desirable, for a high sensitivity, to reduce the distance between the active sensor areas and the material. As the material is moving at high velocities, very small distances result in technical difficulties and reduce the reliability of the measuring system. A 0.5 mm liftoff between the sensor housing and the material was found to be a good compromise between sensitivity and the risk of
material contact, which would result in sensor damage. Liftoffs as low as 0.25 mm are found on resembling measuring systems. Laboratory tests have shown that an increase in liftoff from 0.25 mm to 0.5 mm results in a decrease in SNR of approximately 1.2 dB while significantly increasing reliability.

With crosswise magnetization on moving material, the width of the magnet is limited: The exceeding of a critical value leads to additional signal noise and a reduction of defect signal amplitudes [4]. For material thicknesses up to 500 µm and speeds up to 1000 m/min, a useful magnet width was found to be 69 mm, allocating a 48 mm wide space in its middle with the magnetic field homogenous enough for measurement. As the defined spatial resolution is 1 mm, each sensor module contains 48 GMR sensors. The limited magnet width leads to pole pieces interrupting the sensor line. Thus, the complete surface of the inspected material cannot be covered by one line of sensor modules. As the sensor line width of one sensor module is limited to 48 mm, the modules were designed not to exceed a total width of 95 mm. This allows the whole material surface to be covered by two lines of sensor modules including a tolerance margin of 1 mm per module.

Digitalization is performed at a variable rate of up to 200 kSa/s. With a lengthwise resolution of 0.1 mm per sample, the sampling rate is sufficient for material speeds of up to 1200 m/min. Figure 3 shows a defect recorded by an online test setup containing two sensor modules operating with a reduced sampling rate. Recorded defects are categorized and archived by a long-term storage system.

![Figure 4. Image of defect recorded by an online test setup.](image)

For the prevention of contamination and damage, the sensor arrays are molded into aluminum frames using an epoxy casting compound. Their front is machined to achieve a smooth surface. The machining also reduces the front housing of the individual GMR sensors by 50 µm for an additional reduction of the distance between the measured material and the active sensor areas. That sensor blocks are additionally machined to a precise thickness to be easily interchangeable in case of damage.
Recently (2020), the first full-size test system was installed in a production line. It contains 28 sensor modules, thus covering a maximum strip width of 1344 mm. The modules are arranged in two lines at an angle of 60° to measure on the surface of a single roll. The roll is made of non-magnetic austenitic steel to offer a stability high enough for a precise guiding of the material over its whole width, while not disturbing the measurement. The individual sensor module lines are mounted to water-tempered plates for cooling and to prevent thermal warping. The plates are driven by servo drives and ball screws for an accurate adaptation to different strip thicknesses. Capacitive distance sensors monitor the position of the plates regarding the roll and material surface and trigger a retraction of the sensor module lines if the distance falls below a critical value. The whole system can be pneumatically lifted for the protection of the sensor modules in case of disturbances in the production flow and for maintenance purposes. Additionally, the system can be driven out of line to a maintenance position. It contains a calibration setup for the distance as well as GMR sensors. The distance sensors are calibrated by being pushed against pockets with a defined depth. At the same time all GMR sensors are pushed against circuit boards containing a meander shaped trace. That trace passes every single sensor and is energized by a calibration signal.

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