White Paper

The Benefits of 'Hot' Coating Weight Measurements to Coating Control

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Key Words

Coating weight gauge, coating weight control, X-ray fluorescence, hot dip galvanizing, hot gauge, metal coatings

Abstract

For hot dip galvanizing lines, automatic coating weight control is essential for uniform production with minimized zinc consumption. As production varies from coil to coil, changes in air knife and process settings can be used to manage the transition and optimize yield. This paper describes the ideal architecture for a coating weight measurement and control system which continuously improves its internal control algorithms by comparing the predicted coating weight with measured values. Incorporating coating thickness data from hot and cold sensors, this architecture evaluates long-term modifications in production, and automatically adapts the behavior of the controller to new production conditions. Product changes are handled through a presetting system, which automatically learns data sets during "good" production conditions. For new production runs, the "best" data set is suggested for use with that product. Installations with this coating weight controller have proven that production tolerances can be tightened and production costs reduced. Estimates of raw coating material are presented along with techniques to optimize mill utilization through automatically tightening of production tolerances by changes in target coating weight. These adjustments virtually eliminating scrap between product changeover.

Introduction

Continuous hot-dip galvanizing is an efficient method of coating large amounts of steel strip with a Zinc (alloy) layer. The process begins by heating up the steel and passing the steel through a bath of molten liquid Zinc or Zinc Alloy (see Fig. 1).

With nearly 100 million tons of galvanized steel produced around the world each year, demand for high-quality products continues to be strong. The most profitable products are those which are homogenously coated and produced in a cost-effective way. To achieve this, producers of hot dip galvanized strip strive to optimize their production in regards to quality and costs. The final quality of galvanized strip depends on various aspects such as material surface, zinc adhesion, and uniform coating weight. Proper substrate cleaning and strip temperature control govern the first two parameters, but the third, coating weight, is often measured too late in the process to correct.

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The highest quality products are those with a uniform coating weight and no undercoated strip segments. Since coated coils are purchased based on a target coating weight, coils with any undercoated segments, even a few grams per square meter, are treated as defective goods, they cannot be sold as specified and result in economic losses. The most direct method of reducing material costs associated with coating is to apply the minimum amount of zinc to meet the product specification. Considering quality and potential downgrading costs as mentioned earlier, it is the target to tighten the tolerances of the production to approach the lower specification as close as possible for minimized zinc consumption.

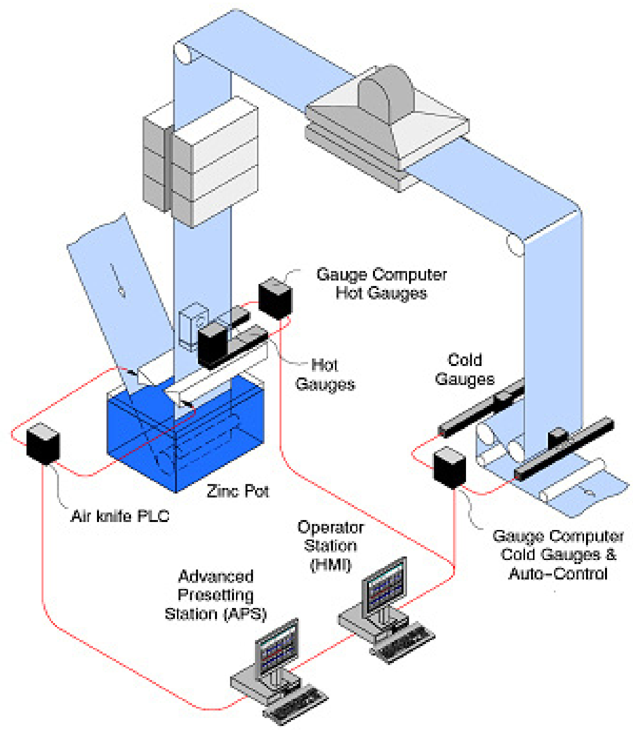


Figure 1: Hot Dip Galvanizing (HDG) Line with Cold Gauge and Hot Gauge Measurements

The standard still used by many to verify hot dip zinc coating weight is based on the Weigh-Strip-Weigh (W-S-W) process described in ASTM A90 or ISO 1460. While this method allows direct traceability to certified international labs, it can only be performed after the coil exits the mill. At this point, if the results are not acceptable the entire coil must be downgraded or scrapped. In the event where the testing is made on a first coil of a new campaign, any adjustments to the process are often made well after the second coil has started, further increasing the amount of scrapped product. Galvanized products with asymmetrical coatings require additional care and time in the W-S-W operation, causing even more of delay in applying any correction.

X-ray Fluorescence Physics

Recognizing this laboratory based verification process can cause prohibitive delays in galvanized sheet production; the majority of producers employ ASTM Standard A754/A754M. This Standard describes a method to determine the coating weight of pure metal coatings on steel by means of excitation of the characteristic X-ray fluorescence radiation caused by the photoelectric effect. This well-known state-of-the-art method is also used as the basis for various other types of measurement, such as evaluating the intensity of several material-characteristic fluorescence radiation energies.

Each element has characteristic fluorescence energies (K-alpha and L-alpha), and associated absorption-edges (Kab, Lab) at slightly higher energies. In practice, only the K series are normally used in coating weight gauges. The primary radiation beam must have some component energies which are higher than the Kab absorption-edge energy of the element required to fluoresce at its corresponding K-alpha energy.

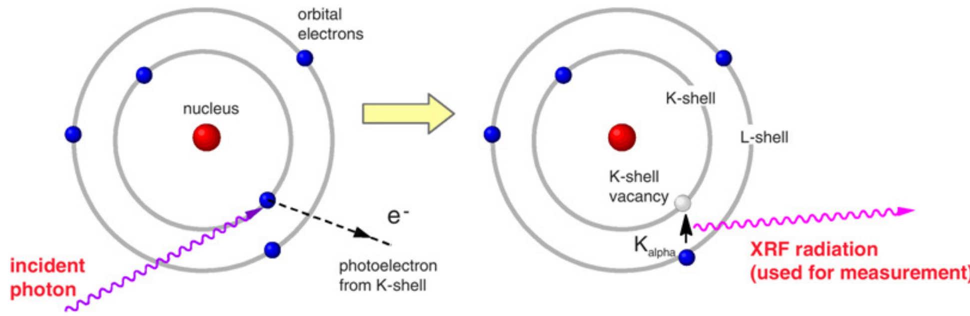


Figure 2: Generation of X-ray Fluorescence radiation by photoelectric effect

For measurement of thin metallic coatings applied to steel strips this X-Ray Fluorescence (XRF) principle is used: The coated steel strip is exposed to a primary beam of photon radiation. This photon radiation can be gamma rays or X-rays, having sufficiently high energy to stimulate excitation and emission (fluorescence) of X-rays. The excitation of iron atoms in a steel strip leads to emission of fluorescence radiation with an energy of 6.4 keV (1 kilo electronvolt = 1.6 . 10-16 J).

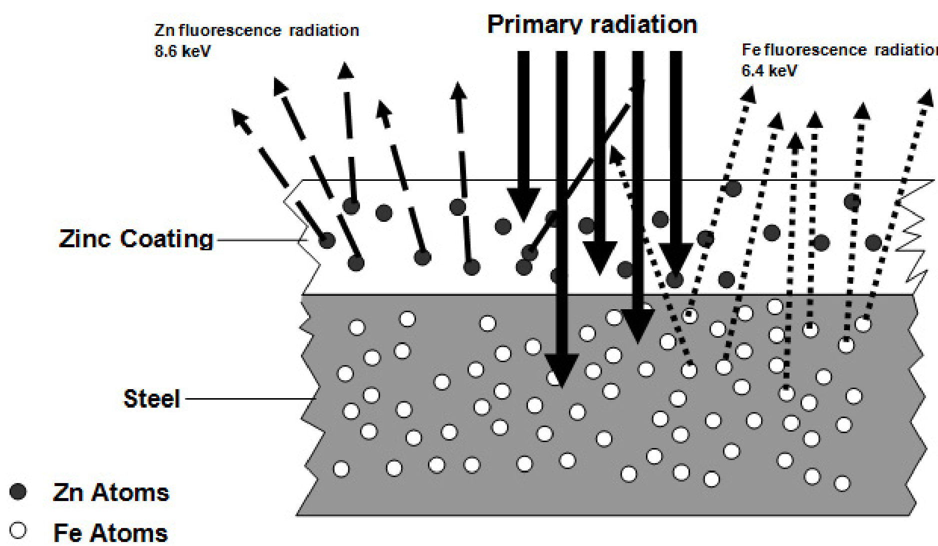
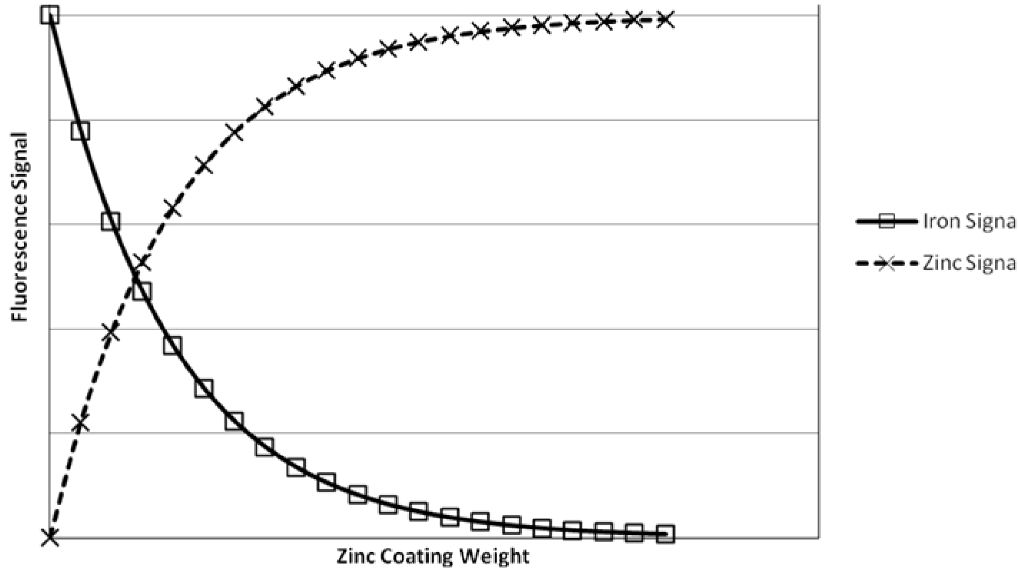


Figure 3: Zinc coating gauge, emission of fluorescence radiation

When the steel strip is coated by another material, the 'iron fluorescence' radiation is attenuated while passing through the coating. If the coating weight increases, less radiation emitted by the steel will pass through the coating. (See Figure 4) It is also possible to use the fluorescence radiation of the coating material to calculate a coating weight measurement. In both cases, specially filtered ionization chambers are used to measure the intensity of one or the other fluorescence radiation.

Figure 4 Zinc and Iron fluorescence signal behavior as a function of Zinc coating weight



Calibration Samples

In order to establish a relationship or mathematical function that converts fluorescence signal to measured coating weight, coating weight standards are required. It is often felt that any galvanized sample can be used, however, because of the inherent errors in laboratory reference procedures for obtaining calibration samples, the calibration of the coating weight gauge is based on a statistical mean (least-squares curve-fit) through the readings obtained from a number of samples. Consequently, the final measurement precision of a coating weight gauge can be better than the known precision of individual samples used for its calibration.

Due to the unique character of individual coating processes, each line should provide all samples required for calibration of their coating weight gauge and for verification of its performance. In the event that samples are not available, the gauge can be calibrated using generic samples. However, the lack of customer provided samples may prevent demonstrating the specified calibration precision of the coating weight instrument. In this case, coating samples should be collected over time, especially from the extreme ends of the typical production range. These collected samples can later be used to further adjust the measurement algorithm.

Once enough samples have been collected, the line operator should identify each calibration sample and its satellites using the W-S-W process. The substrate material and thickness, the coating material, its composition, thickness/coating weight, and estimated uncertainty of stated value should be considered in determining the ultimate accuracy of a X-ray Fluorescence based coating weight gauge.

An ideal set would consist of a minimum of 12 calibration samples, each having nominal coating weights, evenly distributed throughout the specified measurement range, plus one non-coated sample. (See Figure 4) If possible, additional samples should be obtained for coating weights above and below the specified production range. If other coated product types are to be measured (e.g. those having a significantly different substrate material, like AHSS, alloy layer, or surface finish), where it is known that different calibrations will be required, additional complete sets of samples should be collected, including non-coated samples where applicable.

The stated coating weight of each calibration sample should be based on the average of laboratory determined coating weights from four adjacent satellite samples. Ideally, calibration samples can only be considered acceptable when the difference between the satellite samples does not significantly exceed the specified precision of the coating weight gauge itself.

Ideally, the sampling procedure should be as described in the following extract from Section 6.2 of **ASTM Standard A 754/A 754M-96**, and with reference to the sketch below:

Standards - Recommended sampling is to choose a uniform area about 9 by 9 in. (230 by 230 mm). This can be measured by using an X-ray fluorescence instrument to find areas of uniform signal, from which five weigh-strip-weigh (or other reference method) samples are cut in a "cross" pattern, wherein the center sample is in line with two other samples in the longitudinal direction and with two other samples in the cross-sheet direction. If chemical (or other reference method) determination of the coating weight of the four "satellite" samples agree to within about 2%, the center sample can be assumed to have a coating weight equal to the average of the four samples and can be considered a good calibration standard (calibration sample). If standards representing a particular type of coating and substrate are not available from any reliable source, their preparation may be undertaken, but only if thoroughly competent personnel in the fields of analytical chemistry are available.

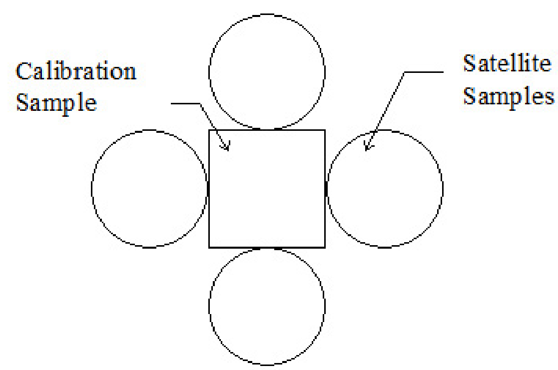


Figure 5: Ideal Calibration Sample Map

Note: As implied above, calibration samples should be discarded when the difference between the values of their satellite samples significantly exceeds 2%.

After a satisfactory calibration set has been obtained, the second set of selected samples should be used to carry out an accuracy check, the records of which must be kept for any future accuracy validation using these same samples. The samples must be carefully stored between protective layers of paper, to prevent mechanical or corrosive surface damage, etc.

Using this calibration method online coating weight gauges have been relatively successfully used on hot dipped galvanization lines since their first introduction over 40 years ago. These first online X-ray fluorescence coating weight sensors were placed after the cooling tower where the strip behavior and temperatures were more consistent. This location provided for stable measurements and when scanned across the strip gave an indication of the edge to edge coating uniformity. Unfortunately, like the W-S-W methods used to calibrate these sensors the measurements are too far after the air knives to see the impact of process parameter changes. In order to react to those changes in near-real time, an online X-ray fluorescence sensor needs to be placed directly above the air knives.

Measurement at the Hot Position of the Galvanizing Line

Coating Weight Sensor Head

The 'hot' measuring heads for coating weight measurement of top and bottom side of the strip are using the X-ray fluorescence measuring principle described above. The sensor head will therefore contain a stable X-ray source, safety shutter, filtered ion chambers and the ancillary electronics to support those components. The sensor head must also provide for vibration and thermal shielding from the harsh environment.

Figure 6: 'Hot' coating weight gauges

The 'Hot' measuring heads also contain further sensors for measuring the distance from strip to measuring head and temperature. Detector housing and measuring head are water-cooled for use up to 100 °C (373 K) ambient temperature. Additionally the detector windows are cooled by air jets.

Distance Sensor

The distance between the measuring head and strip (standard distance approx. 25 mm) is continuously measured to follow the strip movement by a distance control loop with tracking mechanism. The influence of high frequency distance variations due to strip flutter is compensated by software. In those mills with electro-magnetic strip stabilization, the reduced lateral movement of the strip has translated directly to a more stable measurement for the hot gauge sensor, and ultimately a more uniform zinc coating.

Temperature Sensor

A temperature sensor measures the air gap temperature between measuring head and strip to compensate for changes in the temperature of the air gap. Another temperature sensor inside the measuring head checks the internal temperature to generate an alarm if over-temperature occurs and to automatically retract the measuring head from the strip.

Measuring Mechanism for 'Hot' Measuring heads

The measuring heads are mounted on detector arms that can be driven independently to the measuring or standardization position. In the standardization position, coated samples can be measured as well a capability check can be made.

The detector arms can be installed on a moveable base carrier for driving to the measuring position and to the maintenance position beyond the strip zone. For the whole measuring mechanism, a maintenance and installation platform is available. The detector support and drive mechanism, junction boxes and cooling unit on this platform are completely assembled. This will drastically reduce the installation time, which is always important for galvanizing line modernization projects. In special cases the measuring heads are mounted directly on the air knife.

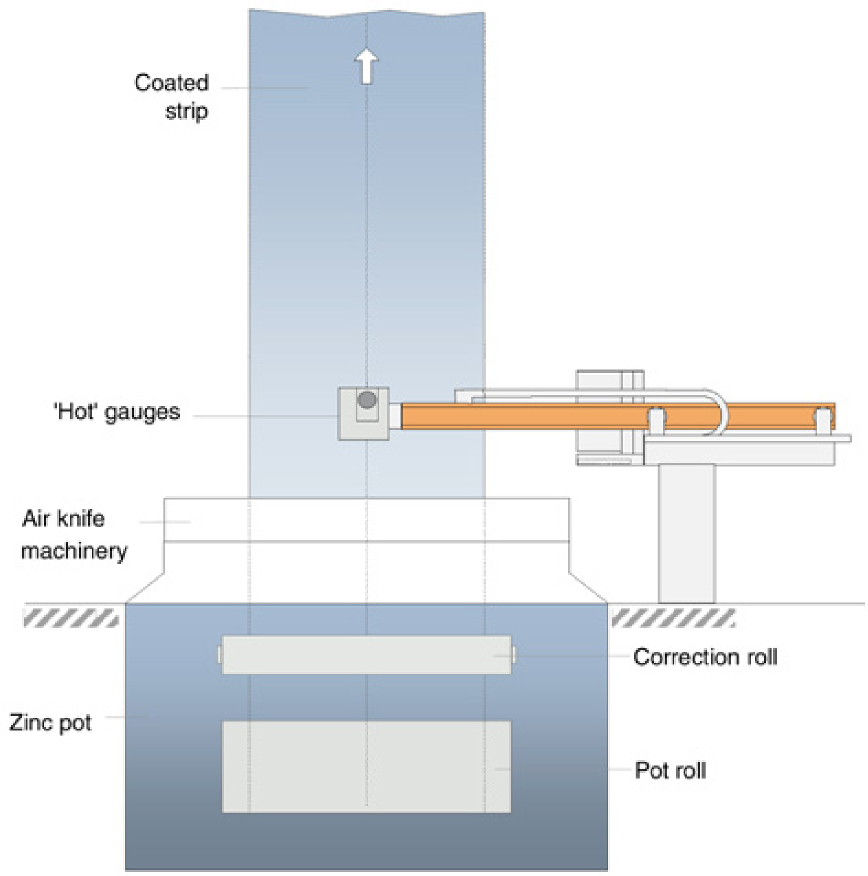


Figure 7: Typical arrangement of 'Hot' gauges

Electronics and operation

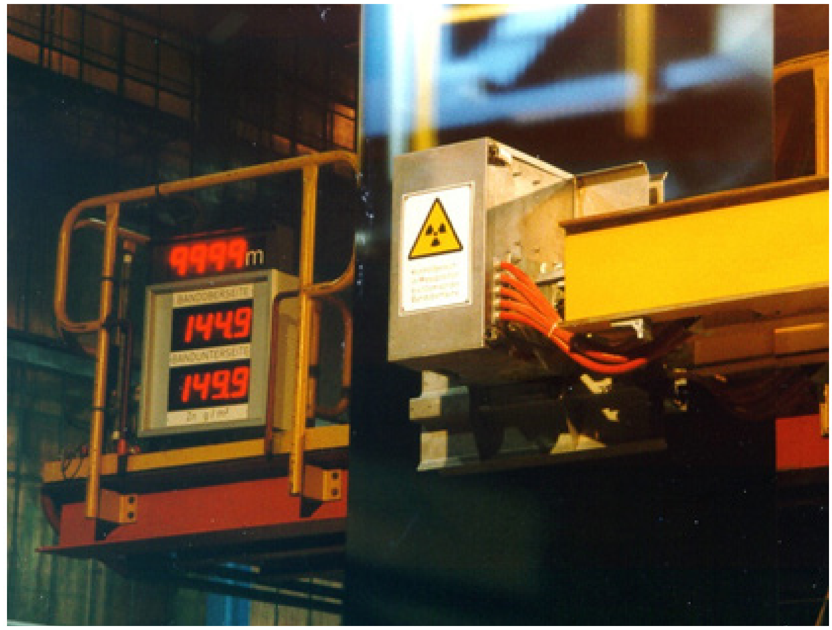
The sensor head does not operate without processing electronics consisting of processor unit, analogue and digital I/O, high-resolution A/D converter and the Ethernet hub. The Ethernet is used for connecting to the coating weight autocontrol system, the operator station and the electronics of the 'cold' measuring system for cascaded control mode. Operators issue commands and monitor coating measurements through logical, easy-to-navigate screens on a PC-based operator station.

Improvement of Manual Operation of the Coating Device

At line start up, e.g. after coating device changes (air knife, bath rolls, etc.) the hot gauge provides an immediate check of the new set-up. The operator can directly see the effects of their adjustments as changes in the measured coating weight of the top and bottom side. In manual mode, each effect of fine-tuning of the coating device (air knife distance, height and angle, pot and correction roll) can be seen within a few seconds. The effects

Figure 8: Immediate check of the adjustments of the coating device.

The actual coating weight of top and bottom side are displayed.

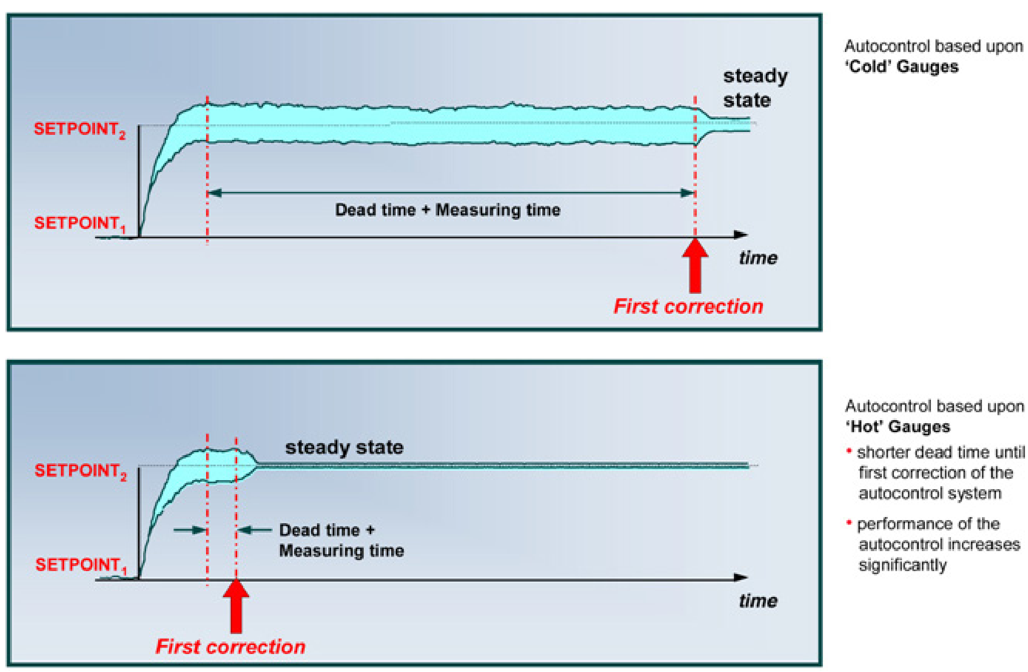


Improvement of Coating Weight Autocontrol by 'Hot' Gauges

Typically, a coating weight autocontrol system is based on the coating weight measurement with scanning cross profile gauges at the 'cold' end of the hot dip galvanizing line.

The position of the 'cold' end measuring system is about 120 m behind the actuator (air knife). At a line speed of e.g. 100 m/min (330 ft/min) the dead time is about 72 seconds. During this time, no feedback control actions can be carried out. (see Figure 9). If a line changes product targets just one time per day this adds up to over 40,000 meters of coil each year.

Figure 9: Reduction of dead time for autocontrol by using 'Hot' gauges



Therefore, effects like off-center displacement of the strip between the air knives or change in roughness of the strip's surface will be recognized too late.

A closed loop autocontrol using the 'hot' coating weight measurement system overcomes these disadvantages. For comparison: the position of the 'hot' end measuring system is only 2 m behind the actuator, with a dead time of only about 1 second. The autocontrol performance increases significantly due to the very short response time of feedback control.

If the measuring equipment consists of both a 'cold' gauge and a 'hot' gauge, the autocontrol can run in cascaded mode. In this case, the 'cold' gauge provides the reference input value for the coating weight setpoints of the 'hot' gauge.

The coating weight controller (CWC) at a HDG line controls the coating weight of top side, bottom side, or both sides together through the physical and mechanical settings of the air knife. This control is based on production parameters received from the Level-2 computer (set points), the measurement values of both coating weight gauges, the line speed, and the air knife parameters (actual air pressure, positions, etc.). Output parameters of the controller are air pressure at top side and bottom side, and the air knife position. Algorithms within the controller continuously calculate the air pressure set points and the air knife position set points based on the production parameter and the process parameters. These calculated values are continuously passed on to the air knife PLC

The air knife PLC together with the entire air knife system forms the underlying pressure control loop for the CWC. Performance of the CWC is assured by short response time and high reproducibility of the underlying pressure control loop. In an ideal situation, the set points of the CWC lead directly to a change at the air knife without any delay, overshooting, undershooting or hysteresis, but, in practice, that is usually not the case.

The air knife parameters (air pressure, position) must be accurately measured, since they are important inputs for the adaptation of the controller and its ability to ultimately optimize production. These parameters are continuously sent from the air knife PLC to the CWC. By receiving the current readings from the air knife, the CWC monitors the actual air knife status versus the assigned pressure and position set points. The communication between CWC and air knife PLC is not restricted to a special link and can be carried out by using various interface types. The most appropriate are Ethernet TCP/IP or Profibus DP. Both methods have been proven and standardized communication protocols exist for various air knives.

Control Features and Control Loops

The CWC is based on an adaptive non-linear process model (adaptive auto control, AAC), which uses the results of the measurement systems for feed-back control. Changes of the material speed and the air knife to strip distance lead to a feed-forward control step. The control steps are based on a process model which can be obtained from the data automatically learned in the presetting system. To improve the base AAC algorithm of the coating weight controller the following control features are available to control the air pressure of the air knives:

• **Cascade Control**

Both gauge systems are used for coating weight control in a combined control algorithm (intermeshed control). New coating weight set points for the hot gauges are calculated by evaluating the average value of the cross profile considering the three spot values. Since the results of the cold gauges are used for the quality reports, the cold gauges are the "master" in the cascade control. In addition to getting the set points from the cold gauge, the controller continues to perform the primary control cycles based on the hot gauge measurement values in order to control fast product variations (either using feed-back or feed-forward steps).

• Target Optimization Control (TOC)

The measurements taken by the gauges are used for a dynamic optimization of the coating target to keep the zinc consumption as low as possible. Through evaluation of the statistical distribution (sigma value) of the coating in machine and cross direction (by a cold scanning gauge), the control set point is adjusted, considering the given tolerance limits and the actual production variance. Production of the coated product will be as close as possible to the allowed minimum coating weight set point (see Fig. 10).

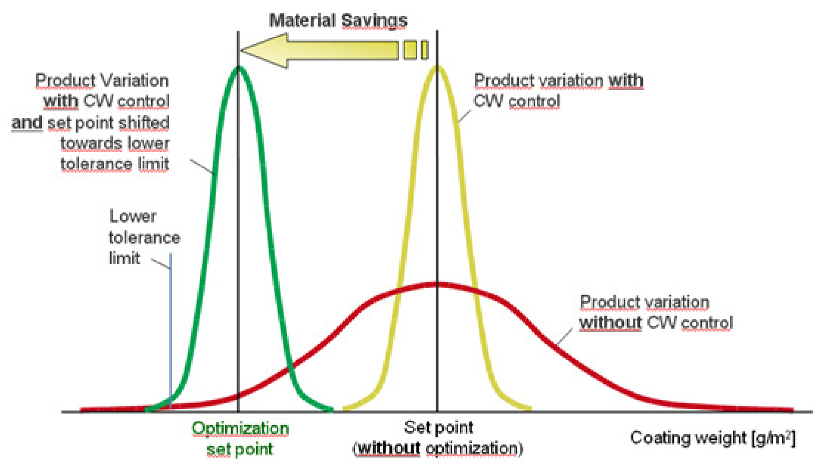


Figure 10: Production without CWC, with CWC, and with TOC

• Sum Coating Control (SCC)

With this control feature, the arithmetic average of the top and bottom target pressures is applied to the air knife system. With both sides of the air knife then operating with the same pressure, 'blowing away' of the strip is avoided. Using this control feature, the sum coating weight is on target, but the top and bottom coating weights may be different. In this case, the air knife distance can then be adjusted either by the operator or automatically by Automatic Balance Control (ABC) as a supplemental feature for the sum coating control. To work completely, the "same spot scanning" function of top and bottom cold gauge is required for systems with two single beam scanners in the cold location.

Model-based predictive Control

Coating weight control is based on a process model. This process model is obtained by a polynomial fit based on the data which is automatically learned by the CWC. In order to adapt the model to the current line situation, a gain factor is used which is continuously calculated as follows:

All process parameters and air knife settings are stored in a FIFO-memory for each defined strip segment along with the predicted coating weight values for this segment. When the material segment is measured, the prediction values are compared with the real measured values. Based on this comparison, the gain factor is adapted. Using this method, the pressure set point will be modified by the calculated factor. The next time this product is rolled, the air pressure set point is corrected so that the prediction value will be identical to the measurement result. By continuously storing the process parameters and air knife settings, the comparison is also continuously executed. With a hot gauge incorporated in the auto-control scheme, this has the great advantage that the long delay time associated with the actual cold gauge measurement does not delay verification of the adaptation process.

Definition of “good” production. When storing data sets automatically, it is necessary to specify the production which should be considered as “good”. For this, the coating weight variation in machine direction and along the length of the coil can be configured.

Searching the best matching data sets. The next coil data is automatically selected by comparing the setup up variables with the stored data sets. The comparison criteria for searching the best matching data sets can be configured. For example, if the variable must be equal to a specific number (e.g. air knife number), or fall within a set tolerance (e.g. air knife distance). An advanced presetting feature (APS) will use the criteria to search the existing preset data sets for most ideal set up for the next coil. To influence the search process, engineers can establish priorities, or weights, for each variable to be used in the search. This search option provides a very flexible tool to operators when handling the technical demands of various coating processes such as Zinc, Galvalume, Galfan, or Galvanneal. Operators can view the current search criteria on the main HMI page of the APS.

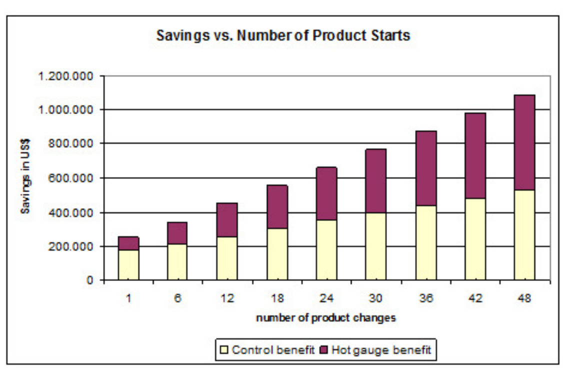
Database Maintenance

Another method to adapt the coating weight controller is to maintain the database of the APS and to eliminate obsolete data sets. If the database keeps only the data sets reflected by the current line conditions, searching for the best matching data is restricted to these sets. This can be either done manually, by using MS-Access, or automatically by the APS software. This function looks for similar data sets (configurable) and keeps the youngest data sets only (number is configurable). By this method, it is assumed that all stored data sets are good and that the line conditions changed over time. The most recent data sets better reflect the most current line condition and should be kept. Automatic maintenance also avoids unlimited growth of the database.

Summary

For a HDG line, including a hot coating weight gauge leads to homogenous and cost-effective production. Auto-control is present in some form on most modern lines and clearly improves the product quality and minimizes the zinc consumption. When dealing with varying line conditions, a hot gauge is in the best position to quickly measure the impact and communicate the true situation to an adaptive coating weight controller. Zinc consumption can be significantly reduced thanks to the use of a hot gauge (see Fig. 11). The savings are dependent on the line condition and on the number of product changes per day.

Figure 11: Zinc Savings vs. Number of Product Changes for Auto-control and Hot gauge



Data used for the Diagram	
Production of coated steel per year	400 000 t/yr
Average strip thickness	1,2 mm
Average coating weight per side	120 g/m²
Zinc price	1643 $/t
Distance Cold Gauge to Air knife	160 m
Distance Hot Gauge to Air knife	2,0 m
Average strip speed	100,0 m/min
Coating Variation CV0 without measurement	10,0 %
Coating Variation CV2 with manual setting	4,0 %
Average Setting time TA of air pressure at air knife	0.12 min

The additional savings by using a hot gauge at a typical HDG line (comparing Cold Gauge with Auto-Control with Hot Gauge and Cold Gauge with Auto-Control) are given in Figure 12. These assumed savings are based on less zinc consumption only (zinc price: 2400 $/ton, July 2012). However, shorter product changes, less scrap, and higher throughput are not considered here and will result in even greater savings.

Figure 12: Savings of Auto-Control (A) and Hot Gauge (B)

Number of product changes per day	A Savings of Auto-Control	B Additional Savings of Hot Gauge	C Total Savings
6	311,000 $/year	188,000 $/year	500,000 $/year
18	444,000 $/year	367,000 $/year	810,000 $/year
30	574,000 $/year	545,000 $/year	1,118,000 $/year

It has been proven in several installations that a hot gauge provides significant added benefit to coating control scheme. There are influences and disturbances not measurable to the air knife mechanical settings that can produce different coating weights with the same process settings (line speed, air knife to strip distance and air pressures). Unchecked by a hot gauge, the resulting coils may have hundreds of meters of downgraded product.

Using a hot gauge, as presented in this paper, the product variation can be tightened shifting the target set point very close to the minimum set point. This leads to a uniform production with minimized zinc consumption and higher profits.

Reference Documents

ASTM Standards

A 754/A 754M-96 Standard Test Method for Coating Thickness by X-ray Fluorescence.

A 630-91 Standard Test Methods for Determination of Tin Coating Weights for Hot-Dip and Electrolytic Tin Plate.

A 623 Specification for Tin Mill Products, General Requirements.

A 624 Specification for Tin Mill Products, Electrolytic Tin Plate, Single Reduced.

A 624M Specification for Tin Mill Products, Electrolytic Tin Plate, Single Reduced (Metric).

A 653/A 653M-96 Standard Specification for Steel Sheet, Zinc-Coated (Galvanized) or Zinc-Iron Alloy-Coated (Galvannealed) by the Hot-Dip Process.

A 792/A 792M-96 Standard Specification for Steel Sheet, 55% Aluminum-Zinc Alloy Coated by the Hot-Dip Process.

A 875/A 875M-96 Standard Specification for Steel Sheet, Zinc-5% Aluminum Alloy Coated by the Hot-Dip Process.

A 428/A428M-95 Standard Test Method for Weight [Mass] of Coating on Aluminum-Coated Iron or Steel Articles.

A 626 Specification for Tin Mill Products, Electrolytic Tin Plate, Double Reduced.

D 626M Specification for Tin Mill Products, Electrolytic Tin Plate, Double Reduced (Metric).

B767-88 (Re-approved 1994) Standard Guide for Determining Mass Per Unit Area of Electrodeposited and Related Coatings by Gravimetric and Other Chemical Analysis Procedures.

A 90/A 90M Test Method for Weight (Mass) of Coating on Iron and Steel Articles with Zinc or Zinc-Alloy Coatings.

White Paper

British (and European) Standards Institution Documents

BS 729 Hot Dip Galvanized Coatings on Iron and Steel Articles, Specification for.

BS 1872 Electroplated Coatings of Tin, Specification for.

BS EN 10142 CONTINUOUSLY HOT-DIPPED ZINC COATED MILD STEEL STRIP AND SHEET FOR COLD FORMING – TECHNICAL DELIVERY CONDITIONS.

BS EN 10147 CONTINUOUSLY HOT-DIPPED ZINC COATED STRUCTURAL STEEL STRIP AND SHEET FOR COLD FORMING – TECHNICAL DELIVERY CONDITIONS.

Federal Standards

FED-STD 151b Metals; Test Methods: Test 513.1 for Weight of Coating on Hot Dip Tin Plate and Electrolytic Tin Plate.

ISO Standards

ISO 1460	Metallic Coatings - Hot Dip Galvanized Coatings on Ferrous Materials - Gravimetric Determination of the Mass per Unit Area.
ISO 2081	Metallic Coatings - Electroplated Coatings of Zinc on Iron or Steel.
ISO 2093	Metallic Coatings - Electrodeposited Coatings of Tin, Annex B.
ISO 3892	Conversion Coatings on Metallic Materials - Determination of Coating Mass per Unit Area - Gravimetric Methods.

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