# A STATISTICAL ANALYSIS OF COAT WEIGHT MEASUREMENTS

by

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Coating weight on a galvanized strip is the function of many different variables, the most obvious being knife pressure, knife distance and line speed. These three variables may be used to make gross adjustments in the coating. However, many other mechanisms are responsible for smaller variations in the coat weight. Among these are strip position, knife skew, crossbow, strip roughness and rolled-in variations in the strip itself.

While it is easy to see gross variations in coat weight, it is often difficult to separate and discern the more subtle effects of the minor variables, many of which are unable to be controlled.

The total variability of coating weight is made up of several layers, like an onion. While we know that there are smaller components of variability in the coating, we are unable to identify their effects because of the covering effect of larger components. To identify these minor components it is necessary to peel the onion, layer by layer.

This paper describes a method of identifying and isolating components of variability mathematically, without eliminating or controlling them. By subtracting these effects from the raw data, we can reduce the longitudinal trend and transverse profiles to identify other components.

We can identify the variations in passline due to strip shape and determine the diameter of the work roll in the cold mill. We can identify variations in galvanneal coatings that point to variations in furnace temperatures. We can isolate the effects of crossbow, skew and passline offset and treat each independently.

The benefits of this analysis are several fold. Operators can determine what portion of total variability is due to strip shape. Engineers may uncover heretofore-unknown sources of variability after stripping known modes. Control systems can be tuned to stop compensating for uncontrollable variations or to minimize their effect on product quality.

## INTRODUCTION

Those who work with galvanizing measurement profile data are accustomed to identifying the common variations in trends and profiles. Gross variations, such as crossbow and skew, are easily identifiable by their characteristic shapes. Cyclic pass-line variations are identifiable in the profile by their characteristic opposition on either side of the strip and more uniform total profile. Passline offset variations may be identified from longitudinal trends as scan averages trend in opposite directions or control adjustments of pressure or distance result in an imbalance between the sides.

The problem with visual identification of coat weight variations is that all variations are not always evident because a large variation from one source may mask smaller variations from others. A still more significant problem may be that control systems, which have been designed to operate on scan averages, may actually be adding variability to the product.

While all variations in coat weight may not be able to be eliminated by control, it is possible to reduce measurement trend data mathematically. This will allow operators to see behind the gross variations to identify more subtle components of variation.

## MEASUREMENT OF ERROR

The most common measurement of variation is the standard deviation. It gives an estimate of the deviation from the mean and permits rule-of-thumb estimates; 95 percent of values are within two standard deviations; 99 percent are within 3 standard deviations.

Statistically speaking, the standard deviation is the root mean squared deviation from the mean. Standard deviation is the square root of the variance, which is the mean squared deviation from the mean. Variance is determined from the sum of the squares of the individual observations from the mean. It is this value, the sum of the squares, which represents total error in a set of measurements. Since it is a squared value, it is possible to think of the total error as an area, the area of a circle. And it is possible to think of that total-error circle being made up of many layers of concentric circles, each representing a different, identifiable source of variation.

SOURCES OF ERROR

Each of those layers of error can be assigned to some cause. Those causes are easy to name: skew, crossbow, passline offset, passline cyclic variation caused by pot equipment or rolled in variations, knife pressure profile non-uniformity, furnace or pot temperature variations, measurement noise, randomness, and others.

Skew

Weight variations due to skew occur when the strip is not parallel to the air knives or the air knives are not parallel to each other. Skew, in its simplest form, is a straight-line deviation from one edge of the strip to the other, equal and opposite on opposite sides. Knowing process conditions, control systems can correct skew by calculating the distance error from the weight difference and the weight/distance gain.

It is possible that skew-like error can be caused by other conditions, such as knife jet profile variations. Adjustments to knife position can effectively eliminate this “phantom” error.

Crossbow

Weight variations due to crossbow occur when the strip is not flat between the knives. In its simplest form, it is a symmetric smooth curve, equal and opposite on both sides. Crossbow can sometimes be corrected by moving the upper stabilizing roll in the pot. The amount of roll-position correction is a function of speed, substrate and process tension.

It is possible that crossbow-like error can be caused by other conditions, such as knife jet profile variations. Whether adjustments to roll position can effectively eliminate this “phantom” error has yet to be determined.

Passline Offset

Passline offset occurs when the strip is not centered between the knives. Offset can be detected by an imbalance in coat weight or, under control, imbalance in the conditions necessary to maintain the target coat weight.

In either case, the magnitude of the offset can be determined by either calculating the distance offset from the weight differential or calculating the offset from the pressure differential. Knowing the distance offset, a control system can automatically adjust the knives or recommend the appropriate correction to the operator for manual adjustment.

Using a coat weight model to calculate offset from actual unbalanced conditions has proven to be the most effective way to determine strip centering.

Strip Temperature

Weight variations due to strip temperature show up, in most cases, as an apparent coat weight variation on galvannealed product. In most cases, this variation will be cyclic, reflecting cyclic variations in furnace temperature about the set point. The variation is most likely to be a change in alloying on the strip and not an actual variation in coat weight, especially when the coat weight gauge does not measure iron content. Differences in alloying will “hide” zinc from the gauge and will appear as a coat weight variation.

Variations caused by strip temperature changes present a problem to the coat weight control system. If the problem is in the ability of the gauge to measure iron, the apparent variation is, in fact, no variation. Any control correction will tend to increase the total variability of the product.

Operations must correct strip temperature variations by tuning the furnace temperature controls.

Pot roll vibration

Pot roll vibration causes the passline to shift cyclically and shows up in the product as a high-frequency oscillation of the coat weight of approximately equal magnitude and opposite direction on opposite sides of the strip. The actual wavelength on the strip will be constant regardless of line speed and equal to the circumference of the pot roll. Frequently, such variation can be seen in the strip as well as be measured by a high-speed gauge.

Weight variations due to pot roll vibration cannot be corrected by a closed loop control system because of the high frequency of variation. Once identified, however, pot roll variation can be corrected by operator action or equipment replacement. A measurement system that is able to discriminate between pot roll vibration and other sources will assist operations in scheduling routine equipment maintenance.

Cold mill variation

Cold mill variations result from shape and tension cyclic variations in the substrate itself. Their nature is similar to pot roll variations and they can be differentiated from pot roll vibrations only by the wavelength of the variation and, hence, the diameter of the causal roll.

Cold mill variation may be caused by work rolls and back up rolls. It is likely that shape variations remain in the strip on subsequent passes and that some longer-period variation may actually be from work rolls on previous passes elongated as the gauge of the substrate coil was reduced.

Weight variation due to cold mill variation cannot be controlled, but it is important for operations to be able to identify it in order to inform the rolling mill.

Blower variations

Blower variations will generally show up as cycles or excursions in the average, affecting both sides in the same direction at the same time.

Weight errors due to blower variations are not controllable because they do not represent sustained changes in coat weight. In actual practice, blower variations degrade the performance of simple closed loop control systems because the system will correct for such variations when they are measured at the gauge.

Air jet profile

Air jet profile non-uniformity, caused by irregularities in knife geometry, will result in one-side sustained variations in profile.

In the best of circumstances, weight variations due to air jet profile may look like one-side skew or crossbow variations and may be able to be corrected using the appropriate mechanism for those conditions.

Strip Roughness

Strip roughness variation is a sustained step change in coat weight on both sides of the strip caused by changes in strip roughness between coils. The step change can be in either direction and may be as great as 10 grams per side.

Weight transients due to strip roughness variation can be reduced using on-line or off-line strip roughness measurements to determine the magnitude of the step and the correction needed.

Random

The remaining variation in the coating, after all known sources have been removed, is regarded as random variation. In its purest form, random variation comes from statistical noise in the process and measurement system.

The “random” variation that we “see” today is not truly random variation. It is true random variation plus many other small-amplitude, indistinguishable variations in the strip preparation and coating process. Statistical analysis and reduction of measurement trends will remove the larger-amplitude variations and make the smaller variations more evident and, hence, distinguishable. This will permit operations to identify and eliminate additional sources of variation.

## ANALYSIS OF VARIATIONS

Variations may be broken down into three major classes; those that affect both sides in the same direction at the same time, those that affect both sides in opposite direction at the same time, and those which are single-side dependent.

Variability can be further classified by whether its source is from variations in the machine direction or variations in the cross machine direction.

### Average

The average trend is generated by calculating the arithmetic average of top and bottom trends.

Average deviations affect both sides in the same direction at the same time. The primary cause of average deviations is strip temperature variations.

The author has seen a furnace temperature cycle in galvannealed product where a temperature cycle of ± 30 degrees resulted in an apparent coat weight cycle of ± 7 grams. Under such circumstances, operations should concentrate on furnace temperature control and not coat weight control. Additionally, laboratory analysis of the metallurgical structure of the coating will identify a preferred coating and help operations determine the preferred strip temperature.

Variations in main blower pressure may also cause average deviations.

### Mirror

Variations that affect opposite sides in opposite directions are called mirrored variations. The mirrored trend is calculated by subtracting the average trend from the trend for the top surface.

Mirrored variations are typically passline variations. These variations may be due to skew, crossbow, non-centered passline or offset, and cyclic variations. Vibrations in pot equipment and rolled-in variations in substrate properties may cause cyclic mirrored variations.

The author evaluated a set of data from one coating line that showed three separate periods of cyclic variation. The shortest of these corresponded to the diameter of the work roll in the cold mill. The others, while identified with a roll diameter, were not as easily attributable to a cause, though likely candidates were the back up roll in the cold mill and the work roll in the cold mill from the previous pass.

### Single-side variations

Single-side, independent variations are most likely caused by variations in the jet profile across the face of the knives. These may be caused by knife geometry or may be short-term effects caused by plugging of the knives.

### Shadow

There is another type of variation -- not mentioned above -- that is associated with passline variations and which we refer to as “shadow”. Rarely do passline variations cause exactly the same weight variation on both sides of the strip, because it is rare that the pressure/distance conditions on both sides of the strip are exactly the same. The distance gain (change in weight for a change in distance) is a non-linear function of pressure, distance and speed. If the distance gains are not equal on both sides of the strip, a given change in passline distance will produce unequal weight changes on opposite sides of the strip. The mirroring function will show equal variation on both sides and the inequality will remain in the average trend as a “shadow”. Operations personnel are familiar with this shadow effect when the total weight profile shows some variation from unbalanced crossbow or skew.

### Machine Direction Variations

Machine direction variations are those which are time or position-based and which act on the entire side of the strip. In single point measurement mode the majority of all variation in the trend is machine direction variation. The remainder may be due to unstable profiles or randomness.

Types of machine direction variation are strip temperature variation, blower variation, pot roll vibration, substrate cyclic variation, passline offset and strip roughness variation.

Cross-Machine Variations

Cross-machine variations are those which vary according to their profile position and are generally reproducible in repetitive scans of the gauge across the strip.

Sources of cross-machine variations include skew, crossbow and one-sided air jet profile variations.

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EXAMPLES

January 20

Figure 1 shows the top, bottom and total coat weight for a set of measurements taken on January 20 this year. The product is galvanized, G40, line speed is 400 feet per minute, strip width is 50 inches, and substrate composition and thickness are unknown. Coat weight target is 70 gsm. There are 559 data points which were taken at a rate of 10 measurements per second and cover 373 feet of material. These data reflect nearly four scans of the coating weight gauge. The data have been scaled for presentation purposes. Vertical scale division is 10 grams.

These data show a strong crossbow effect in the bottom trend, mirrored slightly in the top trend and affecting the total. The angle of the crossbow curve also indicates a skew component.

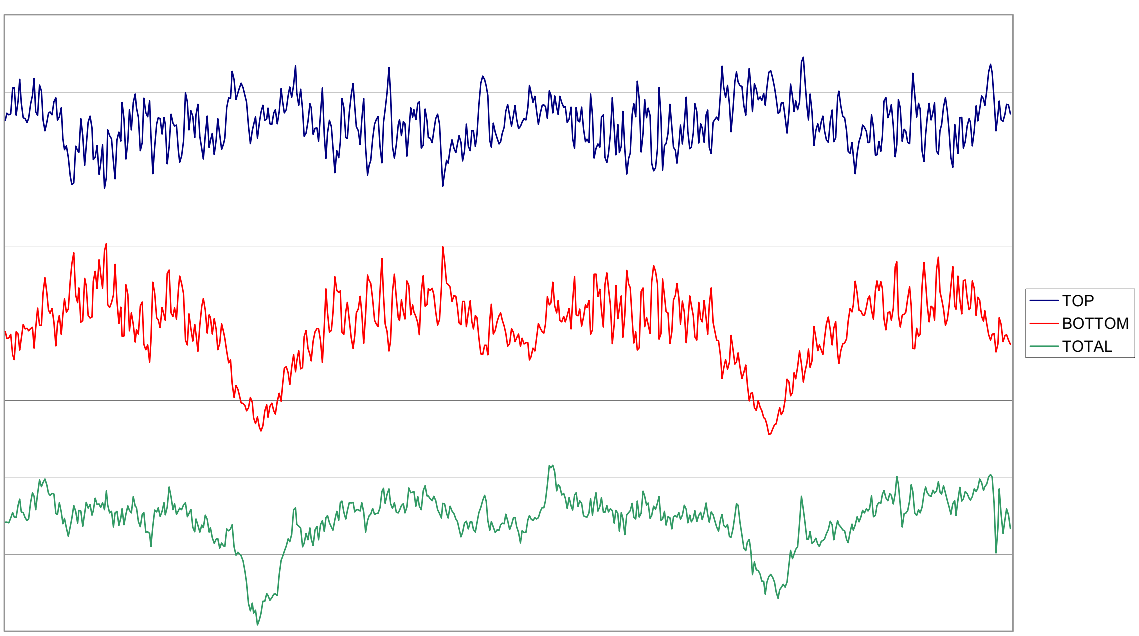


**Figure 1**

Figure 2 shows top, bottom, average and mirror trends. The mirror component shows the crossbow and skew effects that are common to both sides of the strip. The mirror trend contains 77 percent of the total error in the top and bottom trends. Again, the trends are displaced for ease of viewing. The vertical scale division is 5 grams.

The mirror trend contains most of the total variation, which appears as skew and crossbow. A simple skew and crossbow function was calculated for the average profile of the four scans and subtracted from the mirror trend. Figure 3 shows the mirror trend, the skew function, the mirror minus the skew, the crossbow and the mirror minus skew and crossbow. The vertical scale division is 5 grams.

In this reduction, crossbow accounts for 31 percent of the total error and skew accounts for 11 percent. The residual error is 40 percent of the total.

The residual shows strong cyclic variation, much of which is consistent with the scan period, indicating there is still profile-based error. There may also be some shorter period cyclic variation from pot roll and rolled in periodicity. Removal of this error is discussed below.

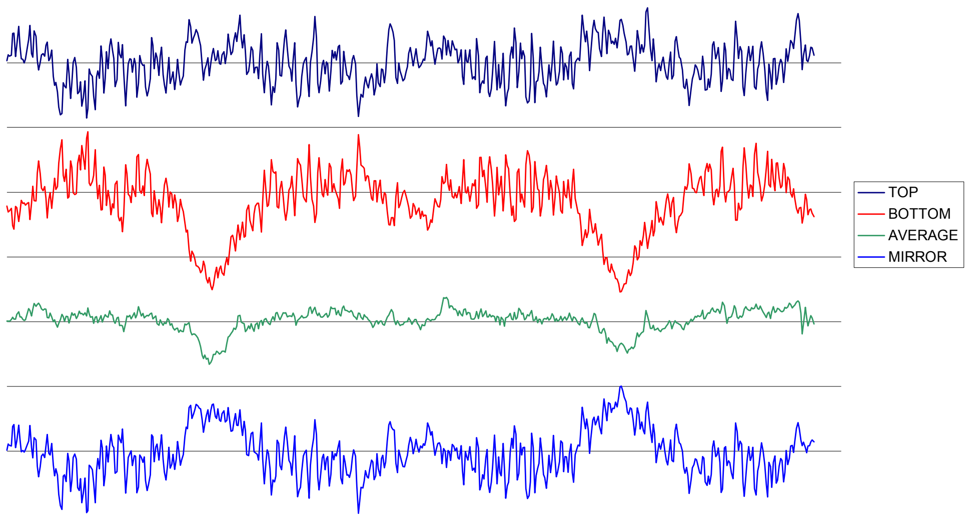


**Figure 2**

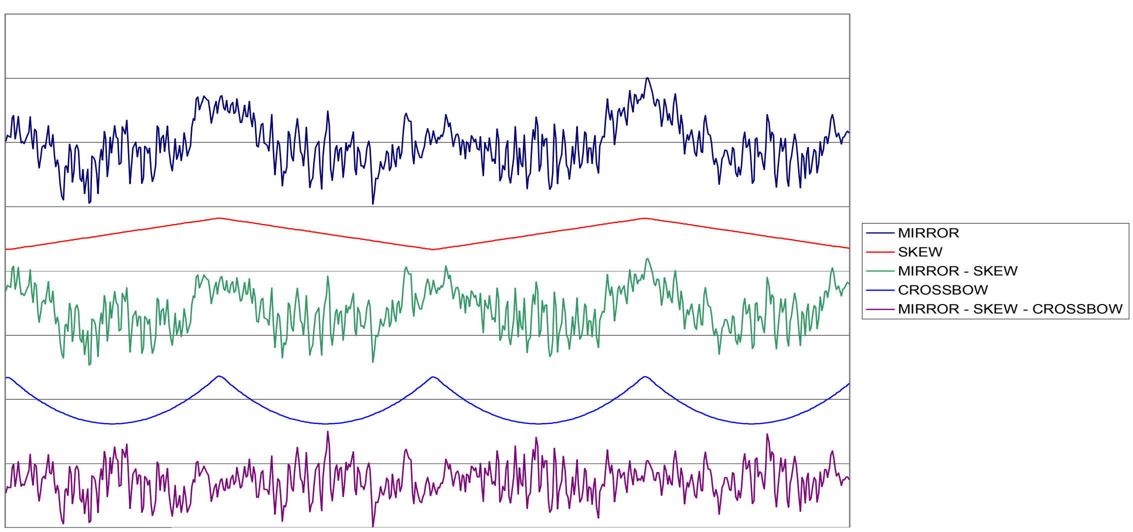


**Figure 3**

August 25

Figure 4 shows the top, bottom, average and mirror coat weight trends for a set of measurements taken on August 25 this year. The product is galvannealed, A45/45, line speed is 240 feet per minute, strip width is 38 inches, and substrate composition and thickness are unknown. Coat weight target is 45 gsm. There are 1185 data points which were taken at a rate of 10 measurements per second and cover 474 feet of material. The total data reflect nearly eleven scans of the coating weight gauge. The data have been scaled for presentation purposes. Vertical scale division is 5 grams.

These data reflect some curious properties. The top bottom and average trends show considerable skew-like and crossbow-like variation, about 5 grams, especially in the bottom trend. However, all three show the same variation in the same direction, indicating that the error may not be true skew and crossbow. While such error could be produced by a strip temperature cycle, it is unlikely that such a cycle would match scanning period exactly. Another possible source of this variation could be air jet profile.

The average shows some cyclic variation of a period much shorter than a scan. The mirror trend shows some periodic variation that seems to be associated with the scan period. There is also some cyclic variation in the mirror trend that is higher than the scan frequency. In this example 75 percent of the error is in the average.

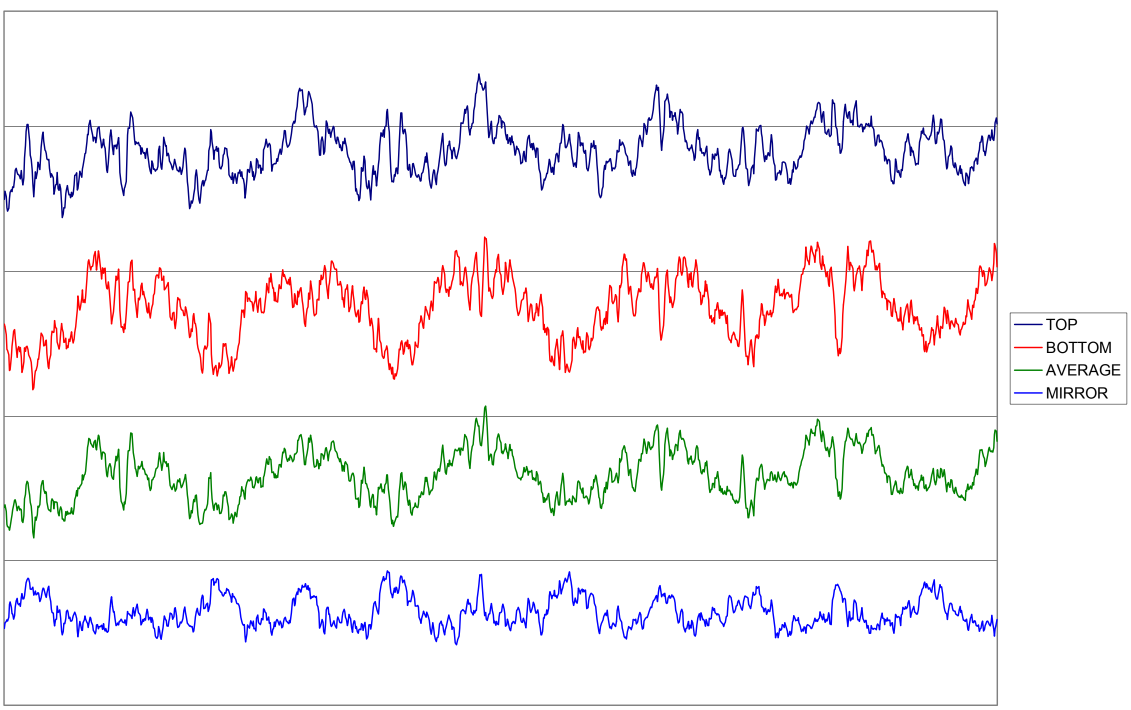


**Figure 4**

August 31

Figure 5 shows the shows the top, bottom, average and mirror coat weight trends for a set of measurements taken on August 31 this year. The product is galvanized, G45/45, line speed is 335 feet per minute, strip width is 52 inches, and substrate composition and thickness are unknown. Coat weight target is 52 gsm. There are 5130 data points taken at a rate of 10 measurements per second covering 2864 feet of material. Four scans, representing 587 points and 328 feet of strip have been extracted for the figure. The data have been scaled for presentation purposes. Vertical scale division is 5 grams.

In this data set there are pronounced edge effects, 5 to 6 grams, in the top trend which are also apparent in the average. There is skew and crossbow evident in the mirror. Both average and mirror show possible cyclic variation. Seventy-five percent of the total error is in the mirror trend.

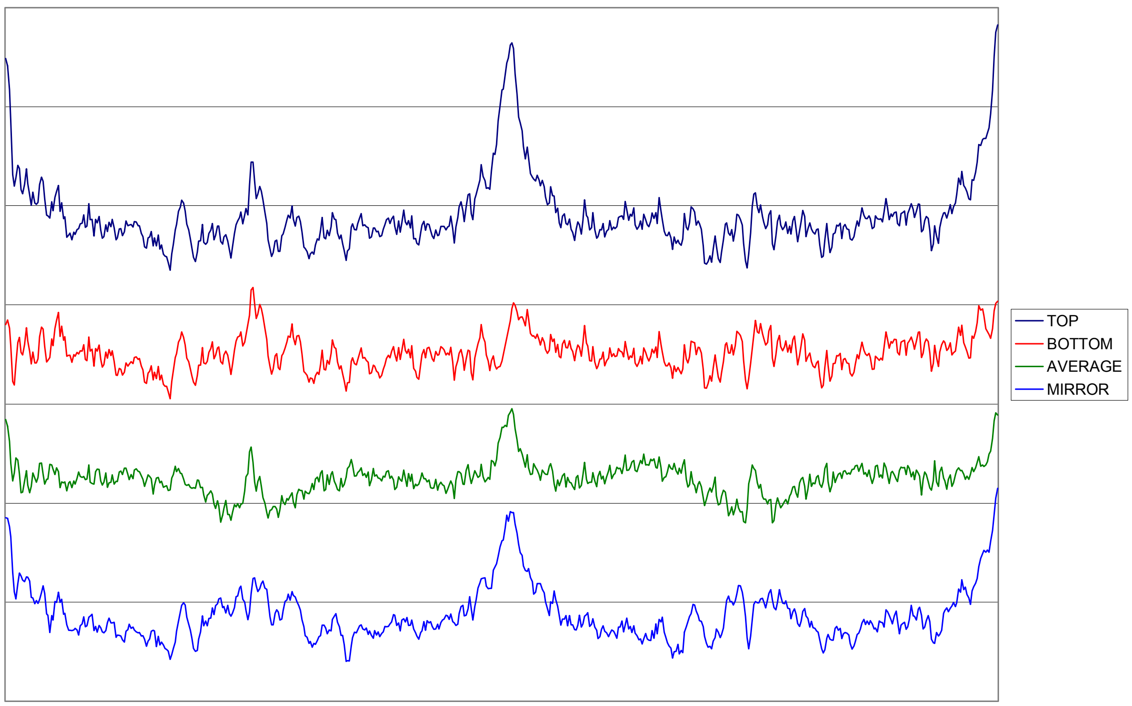


**Figure 5**

September 1

Figure 6 shows the shows the top, bottom, average and mirror coat weight trends for a set of measurements taken on September 1 this year. The product is galvanneal, A40/40, line speed is 205 feet per minute, strip width is 50 inches, and substrate composition and thickness are unknown. Coat weight target is 53 gsm. These 5085 data points cover 1737 feet of material. The total data reflect nearly thirty-five scans of the coating weight gauge. The data have been scaled for presentation purposes. Vertical scale division is 5 grams.

The top and bottom trends show a setpoint change and slow coat weight or measurement drift. Both show skew and crossbow, which is reflected in the mirror trend. There are pronounced edge effects in the bottom trend which show up in both the average and the mirror. The flatness of the average between edges shows that nearly all of the

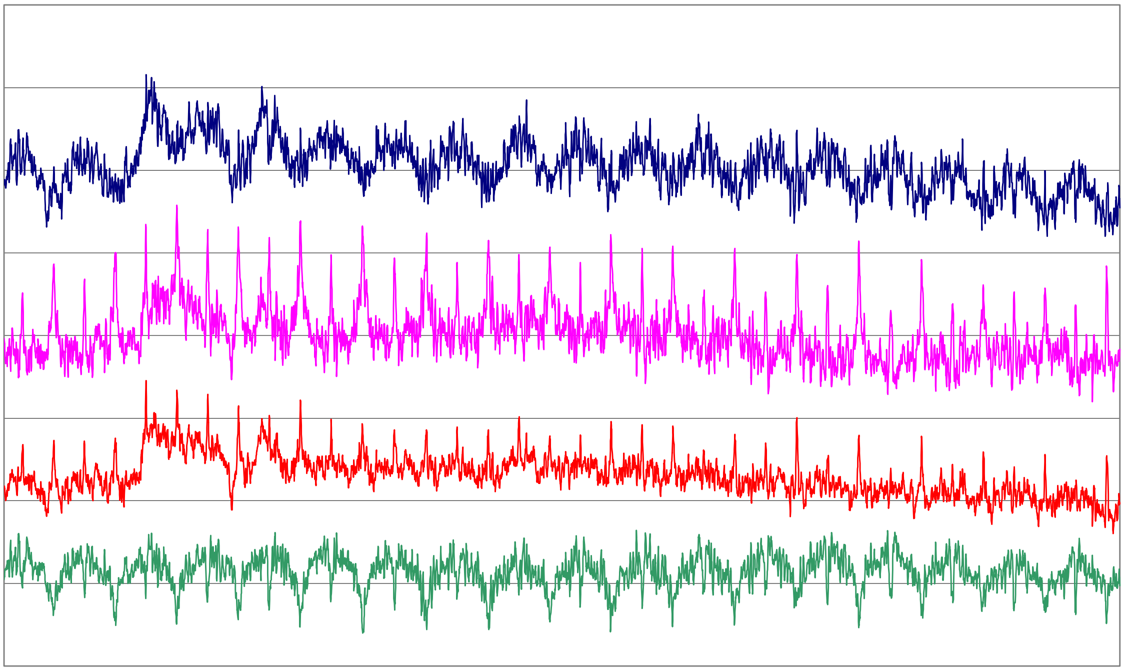

**Figure 6**

skew and crossbow is equal and opposite on the top and bottom sides. Despite its flatness, 60 percent of the total error is in the average, primarily due to the setpoint change and drift.

These data were reduced by subtracting the average profile, which contains skew, crossbow and single-sided air jet variations. The raw top and bottom trends and the reduced average and reduced mirror trends are shown in Figure 7. Virtually all signs of crossbow and skew have been eliminated from the mirror, and a long-period, low-amplitude cyclic variation can be identified.

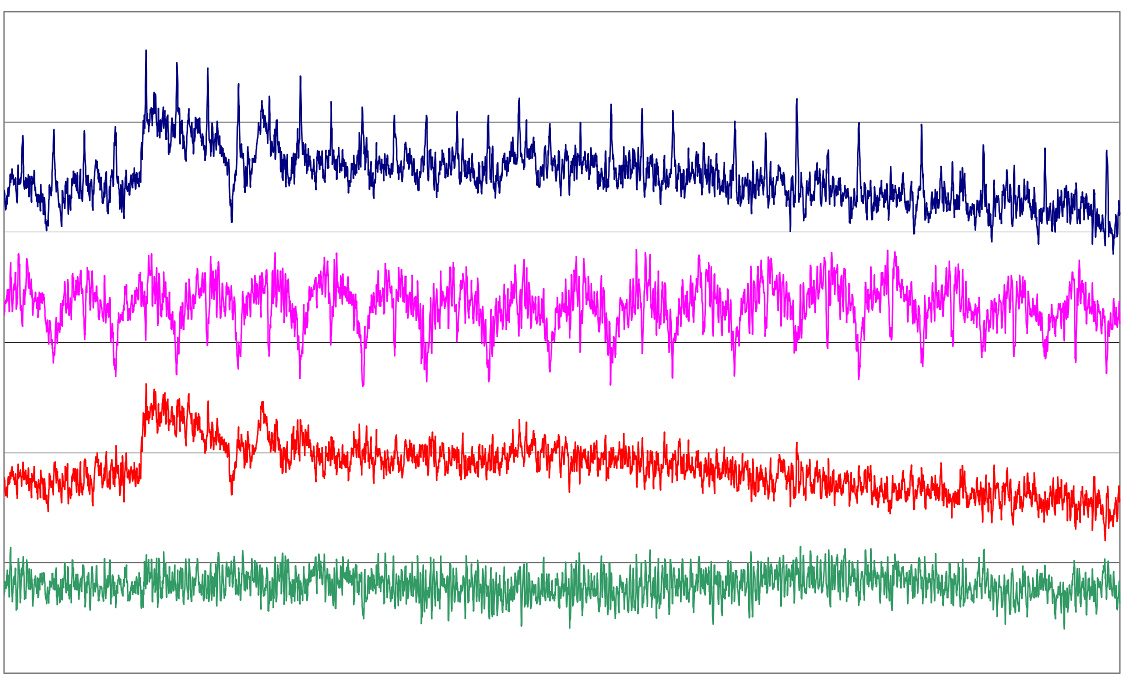

**Figure 7**

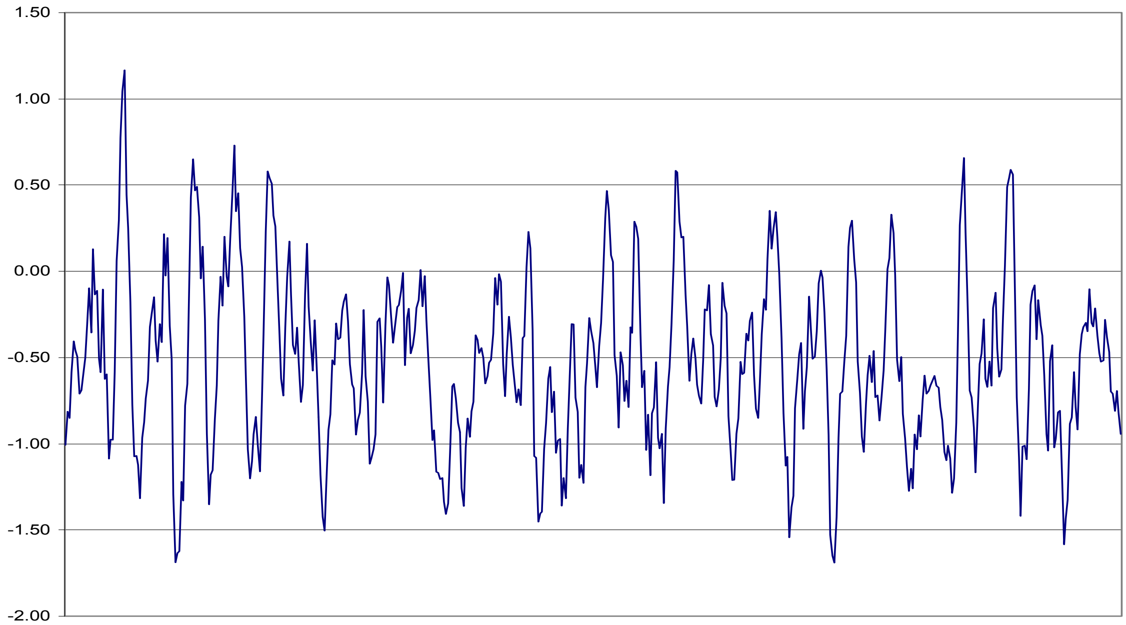


**Figure 8**

Because the data are so dense it is not possible to visually identify any residual short-period cyclic variation, so the data set was reduced to 539 points or four scans. The mirror trend is shown in Figure 8. This trend shows multiple superimposed cyclic variations.

To analyze the periodic variations, Fast Fourier transforms were used to generate a power spectral density chart. Figures 9, 10 and 11 show cyclic the behavior of these data in a variety of ways.

Figure 9 shows the power spectral density plot for the average weight before and after the cross-machine variation was removed. The peaks, which are prominent in the raw data, are virtually non-existent in the machine-direction-only analysis. This shows that nearly all of the cyclic variation in the total is simply repetition of cross-machine variations repeated by scanning.

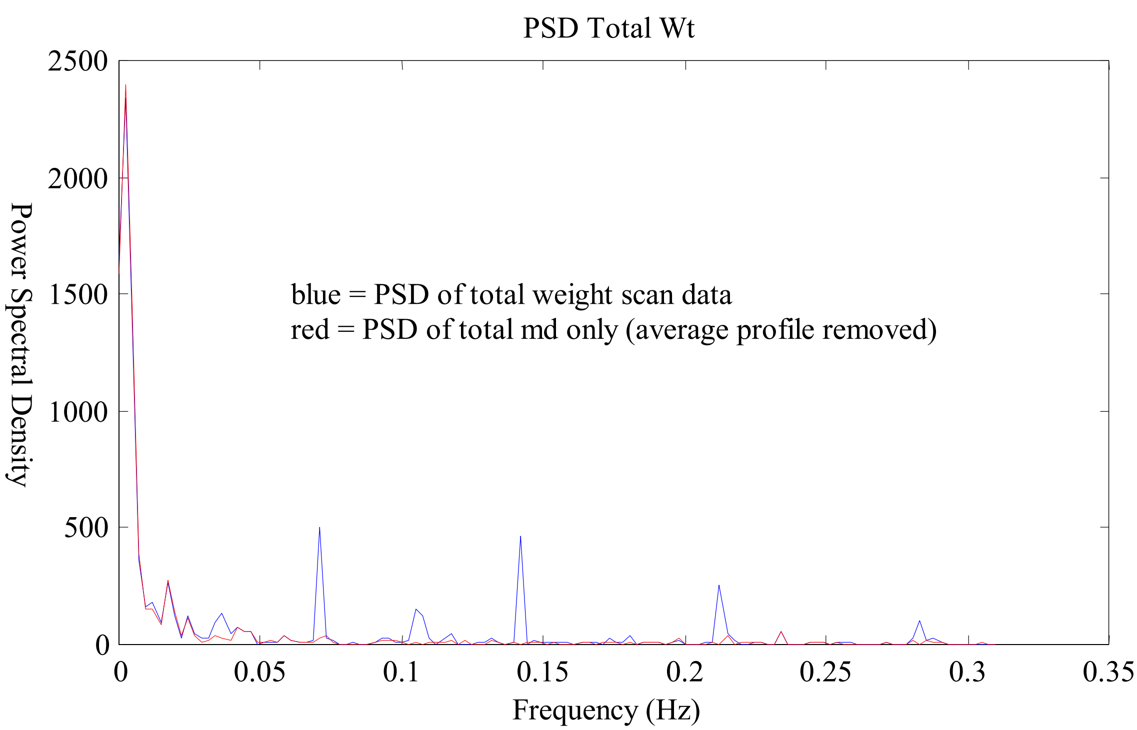


**Figure 9**

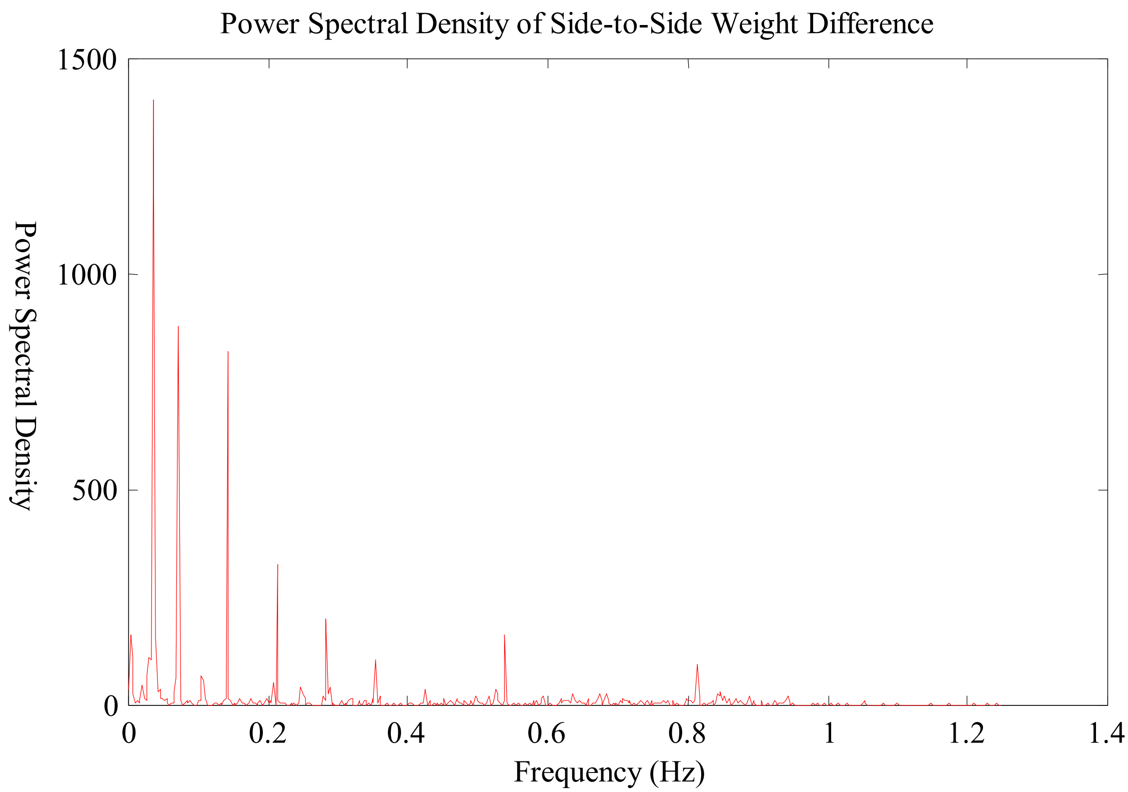


**Figure 10**

Figure 10 shows the mirror power spectral density of the raw data and Figure 11 shows the plot for the machine-direction-only data. Again, the scan-period peaks disappear, but new peaks show up for two higher frequencies, 0.54 Hz and 0.81 Hz. These frequencies correspond to periods of 1.86 and 1.23 seconds, or 6.35 and 4.20 feet. These periods equal the circumference of rolls of 24 inches and 16 inches, respectively.

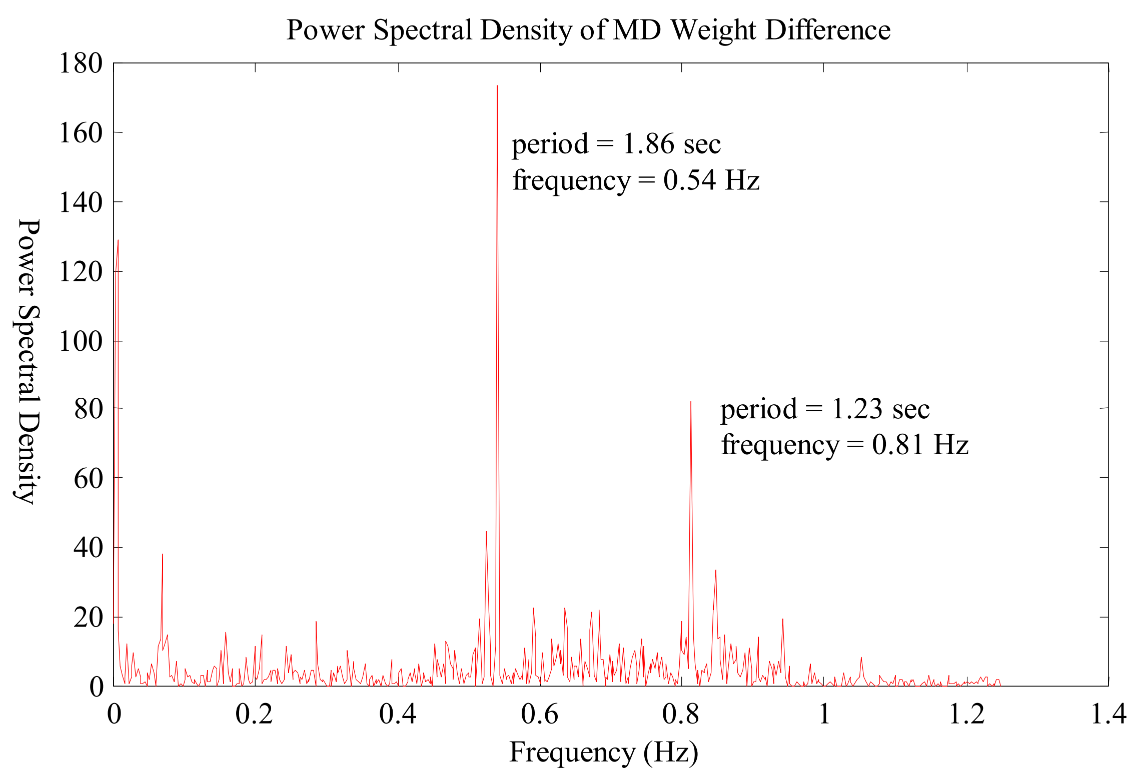


**Figure 11**

CORRECTION OR CONTROL OF VARIATION

Analyzing coat weight variation in the above manner yields two significant results. First, operations personnel have the opportunity to see the influence of each distinct source on total variation. This will permit operations to direct specific efforts at reducing variations. These data reductions show dramatically what operations have suspected for years; that a substantial fraction of total product variation enters the plant as rolled-in variation in the coil. These data analyses will give production quantitative backup in negotiations.

The second advantage comes in controlling the process. Currently, most control systems lump variation from all sources into a scan average, on which control feedback corrections are based. This often requires a general de-tuning of the feedback gain to avoid aggressive control response. By peeling apart the variation by source, it is possible to act on each source independently with a higher-gain, more rapid response. In addition, separating variation by source makes it possible to remove uncontrollable error from the total and act only on sustained upsets which can be controlled. Table I lists the sources of variation, their trend behavior, the direction in which they act, and their controllability.

Errors classified as uncontrollable are so designated because they are not controllable by conventional means. However, adopting different control philosophies, which take advantage of the non-linearity of the process, may reduce the magnitude of some variations. If passline cyclic variation or crossbow is contributing a substantial fraction of the total error, pressures and knife distances may be adjusted to a point where the effect of changes in distance is reduced.

Figure 12 shows the partial derivative of coat weight with respect to knife distance, which is the gain with respect to distance. The partial curves and their associated pressures are; top curve, a pressure of 1.3 middle, 7.3; and bottom, 13.3. These curves show two major influences of pressure and distance control. First, that unbalanced pressures will produce unbalanced process response and second, that the distance gain is more affected by pressure than it is by distance.

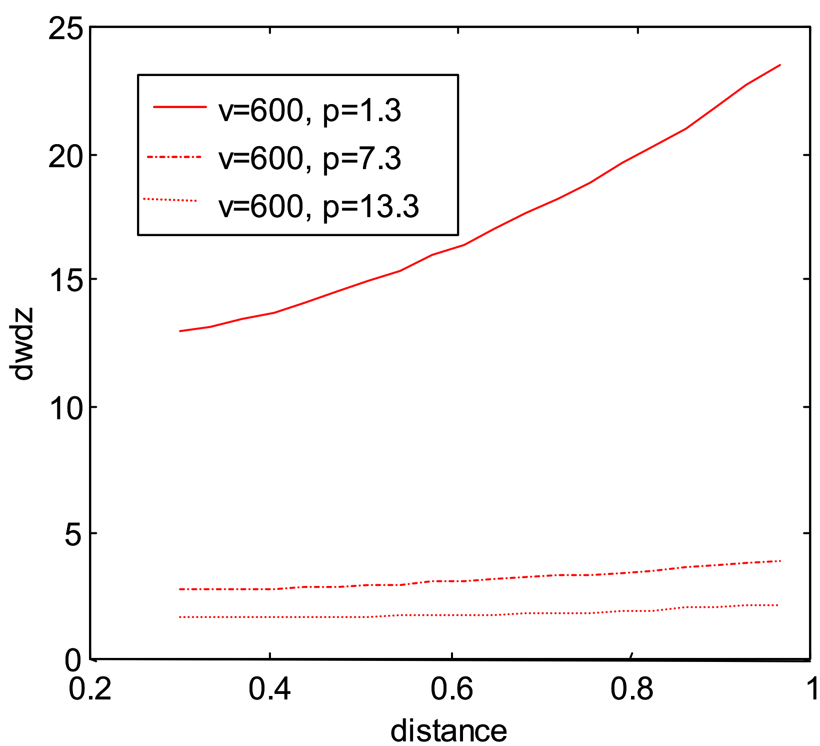


**Figure 12**

## SUMMARY

In an industry where resource prices are rising and customer specifications are tightening, galvanizing operations people need all the help they can get to reduce product variability. By using the methods described to reduce total variation to its component parts, process personnel can arm themselves with accurate data to allow them to purchase, control and deliver superior product.

## ACKNOWLEDGEMENTS

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**TABLE I – CHARACTERISTICS OF VARIATION**

| SOURCE | TREND BEHAVIOR | DIRECTION | CONTROLLABLE |
|---|---|---|---|
| | | | |
| Air jet profile | Single side | Cross machine | No |
| Blower variations | Average | Machine direction | No |
| Cold mill variation | Mirror | Machine direction | No |
| Crossbow | Mirror | Cross machine | Yes |
| Passline Offset | Mirror | Cross machine | Yes |
| Pot roll vibration | Mirror | Machine direction | No |
| Random | Average/Mirror | Both | No |
| Skew | Mirror/Single Side | Cross machine | Yes |
| Strip Roughness | Average | Machine direction | Yes |
| Strip Temperature | Average | Machine direction | No |