

# Minimising the effect of alloy variations on non-contact thickness measurement

*Knowledge of the radiation absorption characteristics of the alloying elements in steels and the relationships between chemical composition variations and measurement errors enables strip thickness gauges to achieve greater accuracy.*

**AUTHOR:** Christopher Burnett  
Thermo Electron Corporation

For centuries, iron has been used in the fabrication of everything from bowls to bridges. Early blacksmiths were highly regarded as having magical powers for manipulating earth, fire, air and water to create such a useful material. Today, metallurgists still tame the four basic elements of matter, but with the knowledge of a host of chemical elements which, when properly mixed, form ultra-strong steel alloys that drive modern productivity.

In a typical rolling mill, the concentration of four or five key elements may define what grade of steel a particular coil is; but to bring out one mechanical property or another, some 30 or more elements may be used. State-of-the-art elemental analysis instruments can determine the weight percent of those elements down to the parts per billion level. Knowledge of the exact product chemistry not only helps determine the mechanical properties of the steel after it is rolled, but when used properly, can optimise the rolling process – increasing quality, saving production time, and reducing scrap.

In the specific case of non-contact x-ray thickness gauges, having the alloy chemistry is required to make a meaningful measurement, but in and of itself does not guarantee gauge accuracy. The influence of the strip chemistry on the final gauge measurement is best understood after a review of the basic theory of radiation gauging.

## ALLOY COMPENSATION IN RADIATION GAUGING

The primary measurement in a radiation thickness gauge is the detector signal. The signal is proportional to the intensity of radiation that passes through the metal strip: as the strip increases in thickness, the detector signal drops, and as strip is rolled thinner, the signal increases. The function of radiation intensity versus strip thickness is represented by Beer's law:

$$I = I_0 e^{-(\rho\mu x)} \quad [1]$$

where  $I$  is the detected intensity,  $I_0$  is the radiation intensity with no material in the gauge,  $\rho$  is the density of the strip,  $\mu$  is the attenuation coefficient based on the strip chemistry, and  $x$  is the thickness of the strip. The formula is easily inverted to determine thickness,  $x$ , as a function of the detector intensity.

$$x = \frac{-1}{\rho\mu} \ln(I/I_0) \quad [2]$$

The measurement  $x$  is relative to a calibration curve made from a base metal, so expanding equation (2) further yields:

$$x_{measured} = \frac{-1}{\rho_{base} \mu_{base}} \ln(I_{coil}/I_0) \quad [3]$$

Substituting back equation (1) relative to the coil yields:

$$x_{measured} = \frac{-1}{\rho_{base} \mu_{base}} \ln \left[ \frac{I_0 e^{-\rho_{coil} \mu_{coil} x_{coil}}}{I_0} \right] \quad [4]$$

Simplification leads to:

$$x_{measured} = \left[ \frac{\rho_{coil} \mu_{coil}}{\rho_{base} \mu_{base}} \right] x_{coil} \quad [5]$$

Clearly if the alloy of the coil in production and the base metal are exactly same, the value in the bracket goes to (1) and the measured value is correct. However, that is typically not the case and a correction factor of the following form is required.

$$Correction\_Factor = \left[ \frac{\rho_{base} \mu_{base}}{\rho_{coil} \mu_{coil}} \right] \quad [6]$$

The compact appearance of this formula masks a great deal when the importance of the attenuation coefficient is explained.

The attenuation coefficient is most easily understood as the probability of a material to stop radiation. The higher the coefficient, the more likely a substance is to stop, or attenuate photons of radiation. The probability of a

material to stop radiation is dependent on three properties, the composition and density of the material and the energy of the radiation. When photons pass through a substance, it is the structure of the atoms that either absorb or scatter the radiation. Heavier elements with their larger atoms and higher densities are better at stopping radiation and typically have larger attenuation coefficients. Alternatively, lighter, smaller elements will have lower attenuation coefficients. Additionally, it is logical to envision lower energy photons being stopped quite easily, but as the energy of the photon increases, the attenuation coefficient drops.

There is one phenomenon regarding the attenuation coefficient that cannot be ignored. It is the obvious discontinuity that occurs where the photon energy corresponds to the energy of the electron shells of the constituent atoms in the material being measured. Each element has a unique electron shell structure, so the attenuation coefficient will abruptly change at a unique energy. *Figure 1* provides a visual example of the attenuation coefficient for two materials, iron and lead. The absorption edges from each are clearly visible, hence for steel alloys with many elements, this requires complex correction factors.

Surprisingly, numerous compensation algorithms have been implemented that virtually ignore strip chemistry and rely solely on check samples of selected alloys. They amount to no more than a look-up table, comparing the grade being rolled to those stored. A single, static correction factor is applied and the exact coil chemistry is not accounted for. These thickness gauges function as a nothing more than a deviation monitor and the list of potential errors in this method are significant.

$$\text{Basic\_CF} = \frac{X_{\text{Actual\_check\_sample}}}{X_{\text{Uncorrected\_check\_sample}}} \quad [7]$$

$$X_{\text{Final\_measurement}} = \left( \frac{X_{\text{Actual\_check\_sample}}}{X_{\text{Uncorrected\_check\_sample}}} \right)$$

$$* X_{\text{Coil\_Uncorrected}} \quad [8]$$

Successful implementation of this compensation method assumes the coil and the check sample have the same chemistry, density and very close to the same thickness. As the differences between the coil and the check

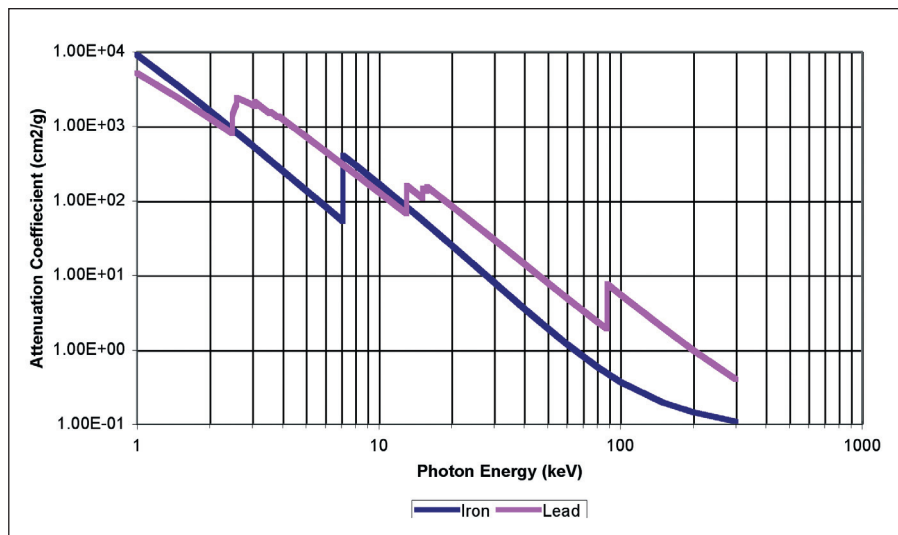


Fig.1 Attenuation coefficients for iron and lead

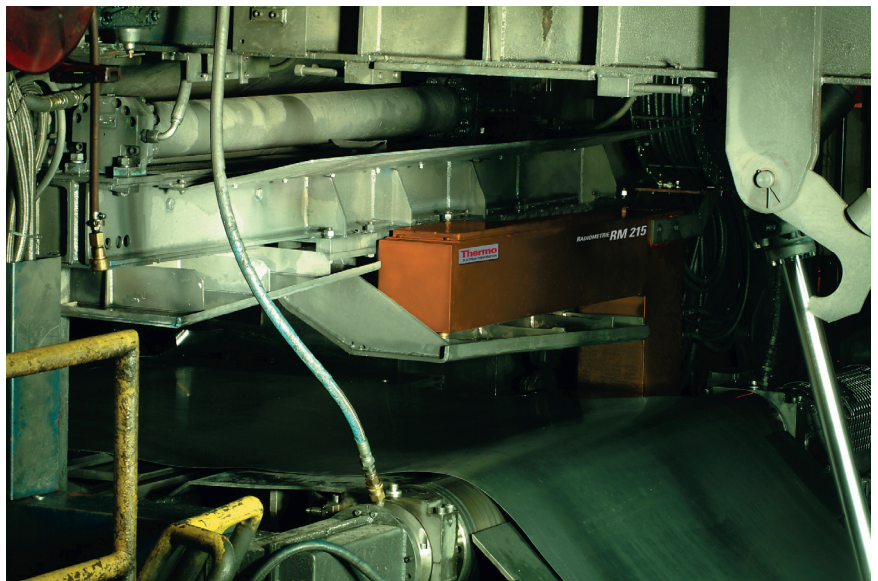


Fig.2 Radiometrie RM 215 high-speed x-ray thickness gauge

sample increase, so does the error. In order for this compensation method to be effective, check samples of every alloy and thickness need to be stored and the chemical composition of coils within the same alloy must be extremely consistent.

On more intelligent gauging systems, the radiation absorption characteristics of each element are integrated into a more thorough alloy correction algorithm. By accounting for individual coil chemistries, these algorithms allow a gauge to extend beyond a secondary role of monitoring and reporting production quality to become a primary instrument in automatic mill control software.

Thermo Electron scientists have reviewed the physics >

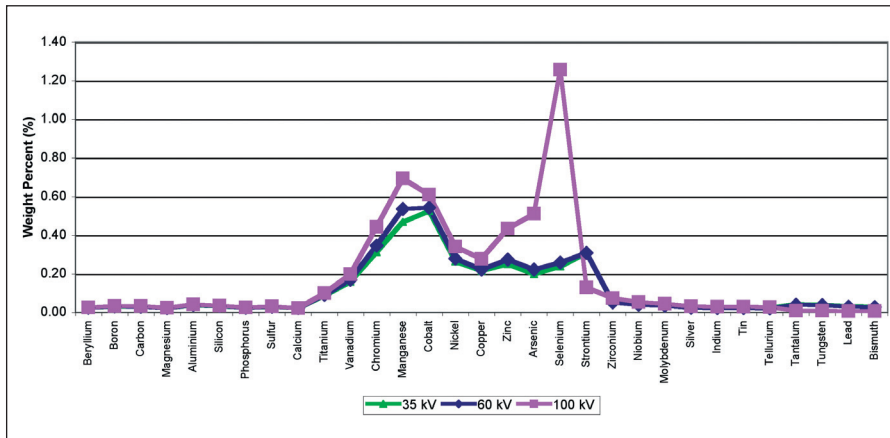


Fig.3 Weight percent error needed to cause 0.1% change in measured thickness

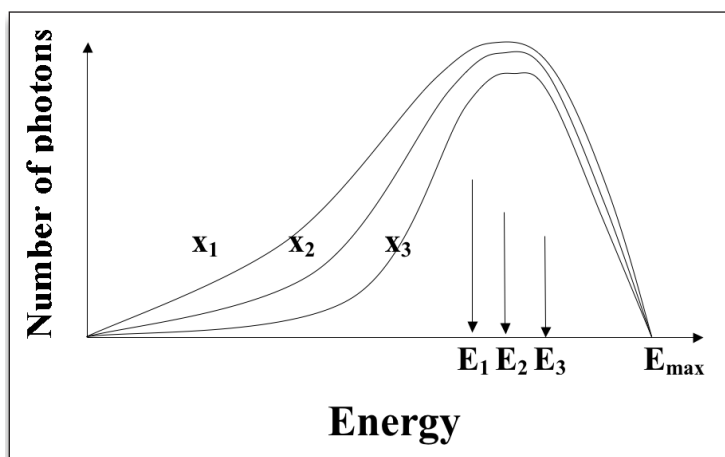


Fig.4 X-ray spectrum

of radiation gauging and modelled how not only the alloying elements affect the measurement accuracy, but how the subtle variations in energy cannot be ignored. They have implemented this correction in the Radiometric series of x-ray thickness gauges, an example of which is seen in Figure 2 installed in a mill. This next step in alloy compensation accounts for each variable in the physical model and produces accuracy levels essential to more sophisticated mill control software.

The attenuation coefficient of an alloy or coil as in equation 6 is determined as follows:

$$\mu_{coil} = \sum_i a_i \mu_i \quad [9]$$

Where  $a_i$  is the weight percentage and  $\mu_i$  is the attenuation coefficient of each element  $i$  in the mixture. Any error in the weight percent of a given element will be translated into thickness measurement errors. The magnitude of that error will depend on the magnitude of the weight percent error and the difference between its attenuation coefficient and that of iron. Figure 3 illustrates this point quite well. It depicts for each element the weight percent error that will cause a 0.1% measurement error. For example, if a coil actually has 0.2% more copper than is thought, there will

be a 0.1% error in the thickness measured. For elements much heavier, or much lighter than iron, the amount of weight percent error needed to cause a 0.1% measurement error is quite small.

Figure 3 also illustrates the energy dependency of the attenuation coefficient. At lower photon energies, the measurement becomes more sensitive to alloying differences, an effect that is accentuated with the spectral nature of x-ray tube emissions.

### BEAM HARDENING

Traditionally, x-ray sources are identified by the electrical potential across the tube. That naming convention is misleading when one considers the continuous spectrum of energies in the x-ray beam itself. When plotting a histogram of the number of x-ray photons at each energy level, the shape would be similar to Figure 4 showing distribution of energies for three increasing thicknesses of samples X1, X2 and X3 and their respective energy levels. No x-ray photons would exist at zero energy and none would exceed the maximum energy applied to the tube. The distribution would be reduced at the lower energy by the absorption of photons by the material used to envelope the vacuum of the x-ray tube (typically this is glass or beryllium). This would leave an average effective energy that is weighted to the higher energies. The integral of this plot  $N(E)$  over the energies from zero to  $E_{max}$ , yields the intensity of the total x-ray beam and is, as stated before, proportional to the detector signal. As material of increasing thickness is inserted into the x-ray beam, the lower energies are preferentially absorbed first and the average energy of the spectrum increases. This phenomena is known as beam hardening and, depending on the energy level of the source and the samples inserted, can change the average effective energy by 20keV.

Such a dramatic change will cause significant changes in the attenuation coefficient as seen in Figure 1. Additionally the rates of change for each element are different, so the influence of each element on the attenuation coefficient will change. If uncorrected, this will lead to errors in compensation. Consider the case described in equation (8). If the static correction factor is restricted by a single thin check sample thickness, but the coil to be measured is much thicker, there will be errors due to the inherent change in energy due to beam hardening. By using the elaborate detector signal processing, Thermo Electron physicists are able to extract the true effective energy of the x-ray beam and recalculate the attenuation coefficient of the alloy for that energy. The calculations have been tested and are robust

## FORMING PROCESSES

enough to effect a compensation throughout an entire measuring range on just one sample. For a multi-purpose steel mill that rolls dozens of alloys, this dramatically reduces the number of check samples required.

**DENSITY**

Returning to equation (6), the attenuation coefficient is not the only variable that must be accounted for. Any complete correction factor must also consider the differences between the density of the base material and the density of the coil being rolled. Unfortunately, the calculation on the part of the correction due to the change in actual density is an approximation and not as accurate. Furthermore, there is no practical way to improve the accuracy of this part of theoretical density calculation itself. The only way to obtain a better value for the density of the alloy is to measure it. This is the idea behind the use of primary alloys, sometimes referred to as parent alloys.

For each primary alloy, samples are made whose thickness and chemical composition are independently determined. The act of creating a primary alloy for the gauge consists of measuring the sample in the gauge and entering the known thickness and chemical composition into the gauge. The gauge then calculates a thickness correction factor for that alloy which is in effect a calculation of the correction due to intrinsic absorption and a measurement of the correction due to change in density. The result is similar to equations (6) and (7), as (6) can be thought of as the correction factor with a theoretical density, and (7) as the correction factor accounting for the actual density. Inverting (6) and multiplying by (7) would leave only the density differences.

$$\text{Density}_{CF} = \left( \frac{X_{\text{Actual\_check\_sample}}}{X_{\text{Uncorrected\_check\_sample}}} \right) * \left( \frac{\mu_{\text{check\_sample}} \rho_{\text{check\_sample}}}{\mu_{\text{base}} \rho_{\text{base}}} \right) \quad [10]$$

where the  $\mu$  values are calculated from (9) and the  $\rho$  values are the theoretical densities determined from the rule of mixtures. Recombining this with (6) again takes to the final form of the physically complete correction factor.

$$\text{Total}_{CF} = \left( \frac{X_{\text{Actual\_check\_sample}}}{X_{\text{Uncorrected\_check\_sample}}} \right) * \left( \frac{\mu_{\text{check\_sample}} \rho_{\text{check\_sample}}}{\mu_{\text{base}} \rho_{\text{base}}} \right) * \left( \frac{\mu_{\text{base}} \rho_{\text{base}}}{\mu_{\text{coil}} \rho_{\text{coil}}} \right) \quad [11]$$

SAE alloy or type	Traditional error (%)	New method error (%)
4118	0.12	0.1 or less
601	0.14	0.1 or less
612	0.21	0.1 or less
652	0.25	0.1 or less
662	0.21	0.1 or less
304	0.36	0.1 or less
316	0.30	0.1 or less
422	0.52	0.1 or less

**Table 1** Comparison of the errors expected over a typical measuring range for common steel alloys

The gauge can then calculate and apply correction factors for other alloys that are very similar to the primary alloy sample in chemical composition, density, and thickness.

**BENEFITS OVER TRADITIONAL METHODS**

The proper method to test the results of this alloy correction algorithm is to select samples of the same alloy through a range of production thicknesses. This would start by selecting one sample as the primary, entering its chemistry and measuring it to record its density correction factor, then measuring the others entering their chemistry if it is different from the primary. While this new alloy compensation method has demonstrated the ability to remain within +/- 0.1% of the actual thickness, errors of the traditional method can approach +/- 0.5% over the same thickness range. It must be stated that traditional methods may choose to collect primary data at every point in the production range, but this requires a very large amount of samples creating cataloging and storage issues. *Table 1* reflects better accuracy using fewer samples which is ideal for modern mills challenged to produce more, higher-quality material at peak efficiencies and at competitive costs.

**SUMMARY**

Thermo Electron's x-ray thickness gauges with their new alloy correction algorithm provide mill operators with an alloy compensation that is truly complete. This accounts for absorption changes that occur not only at the thickness of a check sample of one alloy, but throughout the entire production range of thicknesses and alloys. The resulting accuracy will improve product quality, mill set-up time and therefore overall mill efficiency, each of which is essential to modern-day steelmaking. **MS**

*Christopher Burnett is a Technical Product Manager, Thermo Electron Corporation, Maryland, USA*

**CONTACT:** [metals@thermo.com](mailto:metals@thermo.com)