Development of Alloy Compensation Method for Accurate Thickness Measurement of Steel Product

Jin-Woo Lee[1], Sang-Jin Kim[2], Dong-Gu Lee[3], Gyo-Seong Jeong[1,4], Hyun-Jin Lee[1,4], Sang-Bong Lee[1,4] and Chong-Yeal Kim[5,*]

[1]*Advanced Radiation Technology Institute, Korea Atomic Energy Research Institute, Jeongup-si 56212, Republic of Korea*
[2]*Gwangyang Steel Works, Pohang Iron and Steel Co, Ltd.(POSCO), Gwangyang-si 57807, Republic of Korea*
[3]*Department of Materials Science and Engineering, Yonsei University, Seoul 03722, Republic of Korea*
[4]*Department of Radiation Science and Technology, Chonbuk National University, Jeonju-si 54896, Republic of Korea*
[5]*Department of Science Studies, Chonbuk National University, Jeonju-si 54896, Republic of Korea*

Abstract - Radioisotopes for thickness measurement are widely used in steel-making plants for thickness quality control. During the steel-making processes, several kinds of elements are alloyed in order to meet the required quality for the final products. The conventional alloy compensation methods in thickness measurement are to compensate the thickness deviation of sample acquired at the trial production. This old methods are very limited because there are more alloy steel products in these days. From this project, a high-quality alloy compensation method in thickness measurement is developed in the form of correction equation of each element's weight percentage based on the analyzed data of the MCNP code. Our result shows that new alloy compensation method satisfy the accuracy requirement for thickness gauges, which is ±0.1% of the target thickness. The new method has been successfully adopted in cold finished carbon steel product lines at Pohang Iron and Steel Co, Ltd. (POSCO).

Key words : Alloy compensation, Correction value, Cold finished carbon steel, Radioisotope thickness gauge, Americium, Gamma radiation, MCNP

INTRODUCTION

Pure iron is too soft and easily shaped for many uses to be used in the steel making industry. Iron from the blast furnace is an alloy of about 96 percent iron, with carbon and some other impurities. And, it is converted into steel by removing some of the carbon and adding other metals to produce alloys with properties suited to specific uses. There are many different types of steel, depending on the other elements alloyed to the iron. These days, automobile makers use the alloyed cold finished carbon steel as the basic materials of automobiles or ships. Therefore, most big steel companies are trying to develop manufacturing technology for the new cold finished carbon steel product. In this context, the details of the measurement method and the quality control of cold finished carbon steel product are usually classified as proprietary information. The final thickness of the product is one of the most critical quality factors. The requirement has led to high-accuracy thickness measuring

* Corresponding author: Chong-Yeal Kim, Tel. +82-63-270-3433, Fax. +82-63-270-3434, E-mail. kimbo@jbnu.ac.kr

methods using non-contact radiation from radioisotope or x-ray machines (Lee 2018).

In this paper, radioisotope thickness gauge in the steel industry will be described with respect to the method of alloy compensation. For minor changes in alloy composition can sometimes make measuring errors at final field quality assurance of the final product, we'd like to acquire correction function for alloy compensation and apply it for real production line.

THEORY

The most popular measuring devices for thickness in steel making company is non-contact method using ionizing radiation. This method is based on the understanding of a material's reaction to radiation in a transmission mode framework. Radiometric thickness measurement is based on the principle that radiation energy is absorbed by irradiated material. Radiation emitted by a radiation source passes through material and reaches, weakened by the mass of material, a suitable detector (Lee 2018).

A detector and a gamma radiation radioisotope are located on opposite sides of the measuring material in Fig. 1. The typical radioisotopes for gamma transmission method are Am-241 for cold rolling mill and Cs-137 for hot rolling mill (Liang 2009). The thickness measuring range of Am-241 is from 0.2 mm to 4.0 mm. The incident gamma radiation ionizes the gas within the detector which is ionization chamber. The gamma radiation is attenuated by the target material and the transmitted intensity is measured by the radiation detector. The transmitted intensity $I(x)$ can be calculated from

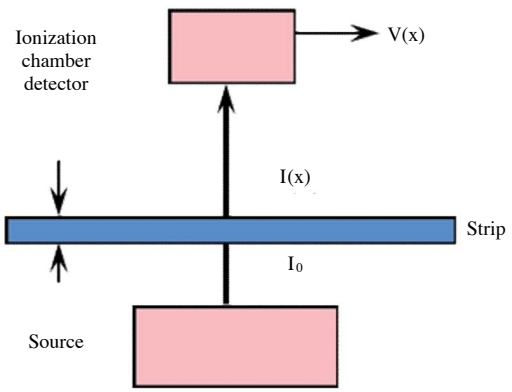

Fig. 1. The basic diagram of gamma ray thickness gauge measuring head.

Equation (1) (J.Kenneth 1996; Glenn 2000).

$$I(x) = I_0 e^{-\left(\frac{\mu}{\rho}\right)\rho x} = I_0 e^{-\frac{x}{q}} \tag{1}$$

Where I_0 is the incident radiation intensity, μ is the linear attenuation coefficient, ρ is the density of the material, q is mean free path, and x is the thickness of the measuring target. And, μ/ρ is mass attenuation coefficient (MAC). The linear attenuation coefficient μ depends upon the energy of the incident radiation and the measuring material's composition.

When the measuring strip is alloyed by a combination of several elements, the weighted percentage of element to be alloyed should be taken into account (Lee 2018). The composite material's MAC is given by Equation (2) and (3)

$$\left(\frac{\mu}{\rho}\right)\rho = \sum_{i=1}^{n} w_i \left(\frac{\mu}{\rho}\right)_i \rho_i \tag{2}$$

$$\left(\frac{1}{q}\right) = \sum_{i=1}^{n} \left(\frac{w_i}{q_i}\right) \tag{3}$$

$(\mu/\rho)_i$: The MAC of the i constituent, of N total constituents

w_i: The decimal percentage of inclusion of the i constituent

$$\sum_{i=1}^{n} = 1.0 \tag{4}$$

The single element relationship of Equation (1) is therefore extended to the composite material

$$I = I_0 e^{-\sum_{i=1}^{n}\left(w_i\left(\frac{\mu}{\rho}\right)_i \rho_i\right)x} \tag{5}$$

To examine the thickness gauge's sensitivity to variances by the alloy of the material, a case which an alloy material is known in, is checked with the low level alloyed material of a non-accounted sample.

Sample #1 - Base alloy which is known to the thickness gauge.

Sample #2 - Another alloyed component of unknown properties such as density, attenuation characteristics and weighting concentrated.

$$\frac{\partial x}{x} = \left[\frac{\left(\frac{\mu}{\rho}\right)_2 - \left(\frac{\mu}{\rho}\right)_1}{\left[\left(\frac{\mu}{\rho}\right)_1 + \alpha\left(\frac{\mu}{\rho}\right)_2\right]} + \frac{\rho_2 - \rho_1}{\rho_2 + \alpha\rho_1} \right] \partial\alpha \tag{6}$$

A key factor in Equation (6) is that the effect of the alloy inclusion is independent of the differences in mass attenuation coefficient (MAC) and densities. This is important, be-

cause MAC has an information related to the spectrum of applied radiation, while the density and alloy information remain independent of radiation (Mark 2010; Lee 2018).

For gamma rays, three interactions are dominant, that is, photoelectric effect, Compton scattering, and pair production. Since we normally use Am-241 low-energy gamma sources for thickness gauges used in cold rolling mills, the photoelectric effect is the only dominant interaction type.

When an Am-241 as a radiation source is used, it can measure the thickness of steel from 0.2 mm to 4 mm. The theoretical alloy correction value is possible to calculate by comparison between the density and atomic number of the base material and alloyed steel of each element (IMS 1997; Thermo-Radiometrie 2002).

The conventional method to acquire correction value is to use the sample of pilot manufacturing. The ratio of thickness deviation between base material and alloyed material can be calibration constant which is used as an input value to the gauge computer. And, it can be utilized as a correction value by approximation. That process should be repeated according to new alloyed steel products (TOSHIBA Corporation 2002).

In this section, the summary of the theoretical basis should be given, if any. Here, you can cite handbooks or classical papers in the field, and use equations, if necessary. Do not use equations which are common knowledge.

EXPERIMENTAL

Monte Carlo calculations were performed using the MCNP 5 code for the typical ranges weight fractions for most popular alloy elements (C, Si, P, and Ni) and five alloy thicknesses (0.2 mm, 0.5 mm, 1 mm, 2 mm, and 4 mm) (TOSHIBA Corporation 2002). Based on these Monte Carlo calculations, this study developed a thickness correction method in the form of a simple equation from the iterative simulation for the measuring condition. The geometry input to the Monte Carlo calculations was provided by the Pohang Iron and Steel Co, Ltd. (POSCO) as Table 1. The final value of measured thickness is affected by the alloy composition of target material. Alloy material mixed to steel product is as Table 2.

The first process is to investigate the influence of each element to alloy correction measurement. The alloy condition of simulation is the maximum mixed one of each element per thickness (0.2 mm, 0.5 mm, 1 mm, 2 mm, and 4 mm). The purpose of this simulation is to check if there is any difference between thickness and correction value in the same element (Lee *et al*. 2013; Lee 2018).

Table 1. Basic thickness measuring conditions

Information	Geometry
Basic material	Iron
Thickness	0.2∼4.0 (mm)
Source	Am-241, 3 Ci
Detector	Ionization chamber (Gas: Argon)
Distance (Source∼Detector)	500 (mm)
Required accuracy	±0.1% (2 sigma level)

Table 2. Alloy element and composition percentage in steel product

Element	Density	Composition percentage
Base (Fe)	7.86	∼99.99%
C	2.25	0∼0.65%
Si	2.35	0∼0.4%
P	2.20	0∼1%
Ni	8.86	0∼2%

Table 3. MCNP simulation of each element with maximum alloy weight

Composition percentage
Pure Fe
Fe (99.35%), C (0.65%)
Fe (99.60%), Si (0.4%)
Fe (99.00%), P (1.0%)
Fe (98.00%), Ni (2.0%)

The basic correction value can be calculated as Equation (7):

$$F = \frac{T_n}{C_n} \tag{7}$$

where F is a correction value of exposure rate of each simulation compared to "Pure Fe" as Table 3, T_n is the ratio of exposure rate matched to "measured thickness", C_n is the interpolated correction factor of "Pure Fe" (Lee 2018).

The number of photon simulation in MCNP was increased to achieve the required accuracy in the real thickness gauge. The average number of simulation histories was 135,000,000 particle histories using F6 tally (Lee 2018).

The second process is to calculate the correction value in weight percentage of each element whose alloy thicknesses are 0.2 mm, 0.5 mm, 1 mm, 2 mm, and 4 mm. MCNP simulations were performed per element with different weight percentages to obtain linear regression curves and regression equations. As a result, the linear function of each element

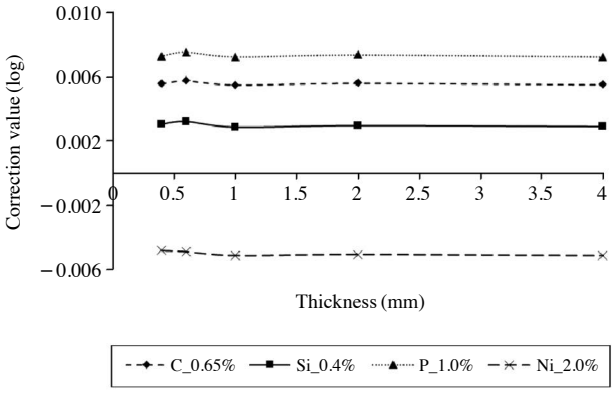

Fig. 2. The plot of correction value with maximum contents of each element in the iron material.

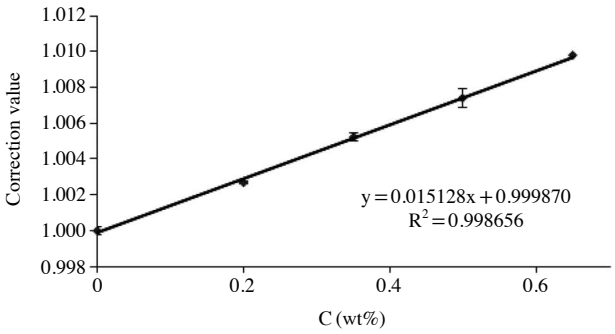

Fig. 3. The regression equation of correction value for carbon alloy.

can be derived (Lee 2018).

RESULTS AND DISCUSSION

1. The influence of each element

The correction value of each element has a positive sign except Ni. It has a negative one due to the higher density compared to iron element referred to Fig. 2. Finally, we found out that the thickness itself affects the final correction value marginally. So, we can conclude that thickness in alloys having other elements is independent of correction value. In addition, we could notice that the weight percentage of each element affects the thickness measurement result (Lee *et al*. 2013; Lee 2018).

2. Linear regression of each alloy element

The linear regression equations between correction values and weight percentages of each element are in Figs. 3∼6 using the regression analysis. As a result, the linear equation

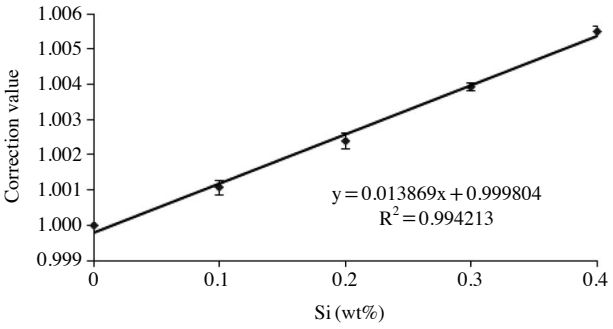

Fig. 4. The regression equation of correction value for silicon alloy.

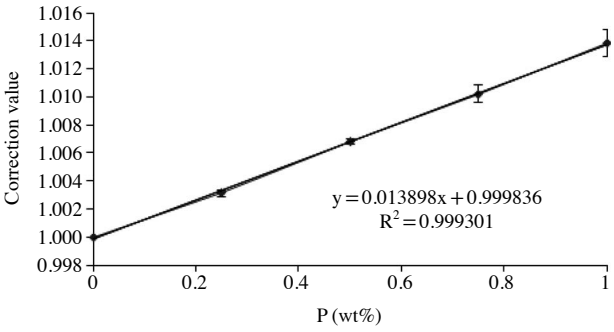

Fig. 5. The regression equation of correction value for phosphorus alloy.

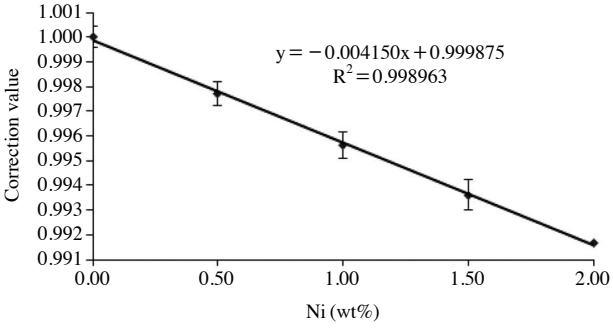

Fig. 6. The regression equation of correction value for nickel alloy.

of each element can be derived. In the regression equation, the values of C, Si, P and Ni are the weight percentage of each element (Lee *et al*. 2013; Lee 2018).

2. 1 Carbon

Carbon is the most important element in steel, it is essential in steels which have to be hardened by quenching and the degree of carbon controls the hardness and strength of steel, as well as response to heat treatment. And ductility, forgeability and machinability will decrease if the amount of carbon increases, as well as welding ability properties of

the steel (Lee *et al*. 2013; Lee 2018).

The regression equation of carbon's correction value as follows:

$$F(C) = 0.015128\,C + 0.999870 \tag{8}$$

where "*C*" is the weight percentage of carbon.

2.2 Silicon

Silicon is one of the principal deoxidizers for steel. Silicon helps to remove bubbles of oxygen from the molten steel. It is the element that is most commonly used to produce semi- and fully killed steels, and normally appears in amounts less than 0.40 percent. However, in steel castings, 0.35 to 0.5% is commonly present. Silicon dissolves in iron tends to strengthen it. Silicon also increases hardness, but decrease in ductility could make cracking problems (Lee *et al*. 2013; Lee 2018).

The regression equation of silicon's correction value as follows:

$$F(Si) = 0.013689\,Si + 0.999877 \tag{9}$$

where "*Si*" is the weight percentage of silicon.

2.3 Phosphorus

Effect of phosphorus element will have various effects on steel depending on concentration. The maximum amount of phosphorus in higher grade steel is between 0.03 to 0.05% due to the fact that is detrimental. Up to 0.1% of phosphorus in low-alloy high-strength steels will increase the strength as well as improve the steel's resistance against corrosion. The possibility of brittlement increases when the content in hardened steel is too high. Even though the strength and hardness is improved, the ductility and toughness decreases. The machinability is improved in free-cutting steel, but weld brittle and/or weld cracks can occur during welding if the phosphorus content is more than 0.04% (Lee *et al*. 2013; Lee 2018). The regression equation of phosphorus's correction value as follows:

$$F(P) = 0.013898\,P + 0.999836 \tag{10}$$

where "*P*" is the weight percentage of phosphorus.

2.4 Nickel

In addition to its favorable effect on the corrosion resistance of steel, Ni is added to steels to increase harden ability. Nickel enhances the low-temperature behavior of the material by improving the fracture toughness. The welding ability of the steel is not decreased by the presence of this element. The nickel drastically increases the notch toughness of the steel. Nickel is often used in combination with other alloying elements, especially chromium and molybdenum. It is a key component in stainless steels but at the low concentrations found in carbon steels. Stainless steels contain between 8% and 14% nickel (Lee *et al*. 2013; Lee 2018).

The regression equation of nickel's correction value as follows:

$$F(Ni) = -0.004150\,Ni + 0.999855 \tag{11}$$

where "*Ni*" is the weight percentage of nickel.

Table 4. Thickness correction coefficients for alloy elements

Element	A_i	B_i	Range of w_i (%)
C	0.015128	0.999870	0.10~0.65
Si	0.013869	0.999804	0.10~0.40
P	0.001398	0.999836	0.10~1.00
Ni	−0.004150	0.999875	0~2.00

3. Derivation of final correction function

The final process is to figure out correction equation in thickness measurement of alloy and to calculate the correction value of real alloy and to compare that value with the sample simulation to verify the reliability of correction equation (Lee *et al*. 2013; Lee 2018).

From regression equations of each element, the final correction equation can be derived as below.

$$Q = \prod_{i=1}^{n} (A_i w_i + B_i) \tag{12}$$

Where w_i is the weight percent of element i and A_i and B_i are coefficients derived from the second process as Table 4.

In practical example, if there are some samples as Table 5, we can calculate the correction value from final equation. And, its result is compared with that of MCNP to confirm the final equation reliability (Lee *et al*. 2013; Lee 2018).

In Table 6, the difference of correction value between $Q(Eq)$ from correction equation and $Q(M)$ from sample simulation is calculated as

$$\text{Difference}\,(\%) = \frac{q(M) - Q(Eq)}{Q(Eq)} \tag{13}$$

And then, the calculated values were compared with the values that were directly calculated by full-fledged Monte

Table 5. Q value from correction equation

Sample	C	Si	P	Ni	Q (Eq)
No. 1	0.6%	0.3%	0.5%	0.5%	1.017576
No. 2	0.5%	0.4%	1.0%	1.5%	1.020216

Table 6. Difference between Q value of sample

Sample	Q (Eq)	Q (M)	Difference
No. 1	1.017595	1.017639	0.006%
No. 2	1.020217	1.020022	0.019%

Carlo simulations. Generally we found that the new method predicts the thickness within 0.02% of error, which is negligible influence on the required accuracy of thickness gauge in this application (Chen *et al*. 2008; Manchun 2009).

4. Application to cold finished carbon steel product

A new alloy compensation method based on the formulas of multiplication derived from regression equation of each element using the Monte Carlo code is applied to the alloy compensation application program of thickness gauge. We also found that the correction factor can be as large as 1% for the ranges of typical weight fractions. Therefore, when we consider $\pm 0.1\%$ of the required accuracy in thickness measurement, this new thickness correction method will significantly improve the quality control of the final product. It is proven that the quality of cold finished carbon steel product has been improved innovatively by using the new alloy compensation method of real-time in gamma ray thickness gauge from the viewpoint of the defect ratio in cold carbon steel product. It can be applied to both old and new steel manufacturing production line.

CONCLUSION

Thickness, which is one of the most important quality factors in steel making industry, is usually measured by an online non-contact thickness measurement system using photon radiations from radioisotope sources or X-ray machines. The measured thickness is corrected for the difference of the alloy composition. When an Am-241 source is used to measure the thickness of an alloy between 0.2 mm and 4 mm, the conventional thickness correction method is based on simple calculations that consider only density change and photoelectric effect. This study develops a highly accurate methodology to correct the alloy thickness for different alloy compositions by intensive Monte Carlo simulations considering the details of the related physics (Lee *et al*. 2013; Lee 2018).

The geometry in the Monte Carlo calculations was based on the dimensions of a specific thickness gauge system at the real iron and steel making company. Based on these Monte Carlo calculations and through reviews of physical process of photon attenuation in material, this study has a target to develop a very accurate thickness correction method in the form of a simple equation. From this study, it was found that the thickness correction factor is almost independent of the thickness of the alloy. It was also found that the thickness correction factor changes linearly with the weight fraction of the elements for all the elements. Considering the additive relationship of mass attenuation coefficients in an alloy, we propose the thickness correction factor be determined by the simple equation (Lee *et al*. 2013; Lee 2018).

Finally, we found out that new alloy compensation method meet the accuracy required for gamma ray thickness gauges. The new method has been successfully adopted in cold finished carbon steel product lines and improve the thickness quality of final product.

ACKNOWLEDGMENT

This paper was supported by research funds of Chonbuk National University in 2018.

REFERENCES

Chen M, Hongmei L, Ziyu C and Ji C. 2008. An examination of mass thickness measurement with X-ray sources. *ARI*. **66**(10):1387-1391.

Denise B. 2010. MCNPX 2.7.D Extensions, Los Alamos National Lab.

Glenn FK. 2000. Radiation detection and measurement. 3rd ed. pp. 53-55. John Wiley & Sons, Inc., Hoboken, New Jersey.

IMS. 1997. Influence of Alloy Components in Radiometric Measurement, Manual unpublished. pp. 2-12.

J.Kenneth S and Richard EF. 1996. Radiation Shielding. pp. 195-197. American Nuclear Society, Inc., La Grange Park, Illinois.

Lee JW. 2018. Development of Alloy Compenstion Method for Gamma Thickness Measurement of Steel. Chonbuk Nation-

al University.

Lee JW, Lee YJ, Kim CH and Choi CH. 2013. A new approach to alloy compensation in a thickness measurement of high-tensile steel. *ANIMMA*. **3**(1):1-5.

Manchun L. 2009. New correction method for dynamic error in on-line gamma ray thickness detection. *ARI*. **67**(1):1974-1976.

Mark EZ. 2010. Radiation Transmission-based Thickness Measurement Systems - Theory and Applications to Flat Rolled Strip Products, Advances in Measurement Systems. Milind Kr Sharma, InTech. pp. 145-148.

Thermo-Radiometrie. 2002. The system manual of Thermo-Radiometrie RM-216M Thickness gauge, Manual unpublished. Thermo-Radiometrie sec1.

TOSHIBA Corporation. 2002. User's Guide for X-ray Thickness Gauge, Manual unpublished. pp. 60-161.

Received: 4 January 2019
Revised: 27 January 2019
Revision accepted: 25 February 2019