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Parabolic Model for Optimum Dry Film Thickness (DFT) of Corrosion Protective Coatings

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Abstract: This study proposes a model for calculating the optimum dry film thickness of corrosion protective Coatings. It was assumed that the graph of coating thickness against corrosion rate is a parabola whose coordinates at turning point consists of optimum thickness and minimum corrosion rate. On this basis, equation of parabola was formed. Three equations of parabola were also formed with three assumed thicknesses, taking arbitrarily with their corresponding corrosion rates of the coated metals. From the equations, a 3x3 matrix was derived. From the solution of the matrix, equations for optimum thickness, minimum corrosion rates and corrosion rate of uncoated specimen were obtained. It is assumed that with this model a technical ground shall be established, upon which the optimum thicknesses of corrosion protective coatings shall be recommended.

Keywords: Optimum thickness, DFT, Corrosion protective coating, Parabolic model

Introduction

Optimization is a process of increasing the precision in measurements of quantities or variables relevant in a system or process in order to achieve most desirable results. One can say that optimization is both technical and economical approach, relevant in all works of life for utmost precision in measurements or estimations of quantities or variables. Optimization of thickness of corrosion protective coating on a substrate is the application of the coating to the most appropriate thickness to ensure maximum performance. It is a way of avoiding wastage of coating material, reducing corrosion rate of the substrate, reducing maintenance rate and ensuring prolonged service life of the substrate. Modelling of optimum thickness of corrosion protective coating is formulation of equations or/and figures that can be used to estimate the optimum thickness. However, the major reason for optimization of thickness of corrosion protective coatings is to ensure prolonged service life of the substrate by minimizing its corrosion rate via protective barrier (coating).

Corrosion is one of the major challenges associated with the use of metals and alloys. It is the degradation of metals in aggressive environment [1]. Corrosion occurs in two ways, the galvanic and electrolytic processes [2]. Steel corrosion involves series of reactions that convert iron into iron oxide (rust). Forms of corrosion include general, intergranular, pitting,

crevice, erosion corrosion and others [3]. All forms of corrosion reduce the mechanical properties of materials especially the strength. Thus, corrosion likely impairs the overall quality of materials. Nevertheless, so many corrosion mitigations measures have been developed. The use of corrosion protective coatings amongst other methods had been discovered as an effective method of corrosion mitigation [4]. Several researchers have attempted to study the performance of corrosion protective coatings and have come up with interesting results. A typical example was shown in Curkovic *et al.* [5]. In recent time, many industries use coatings to protect metal components against corrosion as given in some articles [6, 7]. Coatings are applied on car bodies, underground and surface tanks, ship bodies, pipelines and others. However, it had been noted that coatings suffer failure due to flaws associated with coating thickness. Such defects include cracking, porosity, delamination, pin holes, sagging, brittleness and orange peels [8-10]. All these defects reduce the quality and performance (durability) of coatings. According to J. Lichtenstein, the service life and performance of coating greatly depends on its thickness [11]. Previous studies show that excessive thickness of coatings can cause cracking, delamination, sagging, porosity, while insufficient thickness can lead to cracking, pin holes, exposure of the substrate etc [12, 13]. Tan *et al.* [14], studied the mechanical properties and microstructure of Ti6Al4V coating on Ti6Al4V substrate over varying coating thickness, the results obtained showed no

significant change in mechanical properties such as hardness and adhesion strength. However, increase in coating thickness resulted in increase in porosity (from 2.7 to 3%) which indicates that the service life and performance of the coating might be influenced negatively. Iron-based amorphous coatings have been found as effective corrosion protective coatings [15], [16]. In a study [17], the impact behaviour of Fe-based amorphous coating with various thicknesses applied by high velocity air-fuel thermal spraying was investigated through 3D X-ray tomography. The results showed that impact damage occurred mostly due to cracks in the coating, plastic deformation of the substrate and delamination at coating/substrate interface. It was also shown that delamination size is a nonlinear function of normalized coating thickness (i.e. ratio of coating thickness to contact radius). Similar research was conducted by Sukarman *et al.* [18]. In this case, powder coating process parameters were optimized to improve the dry film thickness of powder coating on mild steel using RAL 7040 epoxy-polyester at coating thickness in the range 70 to 100 microns. An orthogonal Taguchi L16 array of independent variables was used for analysis of experimental results. The experimental result shows that optimization of process parameters gives improved coating thickness of better performance. Also, in another study [19], the influence of anticorrosion pigment, dry film thickness and conditioning time on protective properties of Two-Component Epoxy Primer was investigated. The results obtained show that the content of the anticorrosion pigment has a great influence on the coating performance, followed by coating thickness whereas conditioning time has less effect. Graphical plots of zinc coating thickness against the service life in various exposure environments, within a specified range are given as Figure 1.

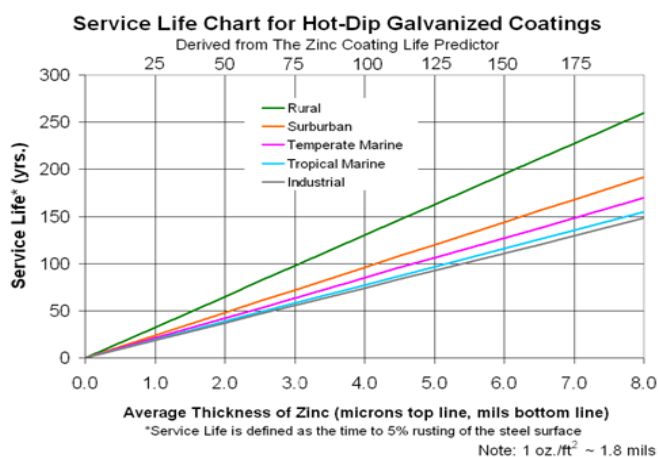


Figure 1 Plots of zinc coating thickness versus the service life in various exposure Media [20]

Looking at the consequences of applying coatings outside the appropriate thicknesses, it is of paramount importance to establish a technically acceptable procedure for recommending range of thickness for various coatings and for specific uses. Many industries recommend certain range of thickness

for various coatings. For instance, Marlin Steel Wire recommends 0.032 to 0.058 inches for polyurethane coating [21], Raha Bitumen Company recommends 24nm for bituseal [22]. FERRUM S. A. recommended minimum thickness of 80nm, 250nm and 1.8 -3.7mm for epoxy layer, copolymer layer and polyethylene layer respectively for a three-layer coating [23]. Also, in FERRUM S.A., it is stated that the properties of the coatings comply with EN-PN ISO 21809, DIN 30670, DIN 30678, NFA 49-710 and EN-PN 10285 and other relevant specifications [23]. However, there were no technical reasons given for the thicknesses recommended. Thus, there is need to develop mathematically based procedure, through which one can recommend thickness of coating for corrosion protection of metals. One way of achieving this is by determining the most effective thickness of coating, otherwise called optimum coating thickness. It is believed that use of optimum coating thickness will guarantee best performance.

Some researchers have attempted to propose methods for determining the optimum thickness of corrosion protective coatings. In Winnicki *et al.* [24], a logarithmic model, popularly known as Taguchi method was given, in which Low Pressure Cold Spray (LPCS) technique was used to produce anticorrosive coating, whose dry surface has varying thickness given in wavy topography. Also, Aisyah [25] gave a model in which the optimum thickness of insulation was deduced from the graph of temperature change between surface of insulated pipe and ambient temperature against coating thickness. Optimum thickness can also be estimated as the minimum point of the graph of coating thickness versus edge-bead ratio [26]. Mathematical models for dip coating thickness and spin coating thickness have also been given in a published article [27].

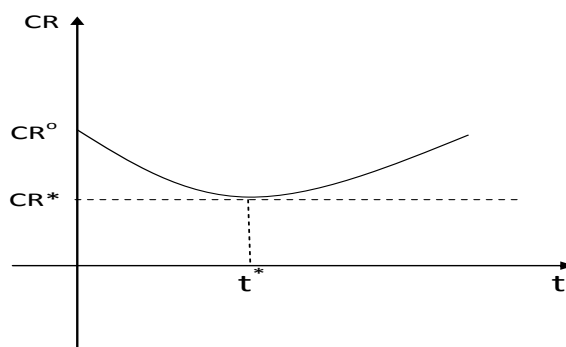


Figure 2 Schematic of proposed parabolic model for optimum thickness of corrosion protective coatings

In all the cited articles, the effect of coating thickness on corrosion rate of the substrate was not considered. In this study, a model has been proposed, assuming the graph of corrosion rate of substrate against coating thickness is a parabola whose coordinates at turning point consist of optimum thickness and minimum corrosion rate. Schematic of the graph of

corrosion rate versus coating thickness is given as Figure 2.

$$t^* = \frac{1}{2} \left[\frac{(t_2^2 - t_3^2)(CR_1 - CR_2) - (t_1^2 - t_2^2)(CR_2 - CR_3)}{(t_2 - t_3)(CR_1 - CR_2) - (t_1 - t_2)(CR_2 - CR_3)} \right] \quad (10)$$

Derivation of optimum thickness

From Figure 2, the optimum coating thickness may be derived from the equation of the parabola given by:

$$CR - CR^* = at^2 + bt + c \quad (1)$$

where CR is corrosion rate of specimen taken at arbitrary point, t is coating thickness taken at arbitrary point. CR^o is the corrosion rate of uncoated specimen (when t = 0), CR* is corrosion rate of specimen with optimum coating thickness, t* is the optimum thickness of coating, a, b and c are constants.

Dividing both sides of (1) gives:

$$\frac{CR - CR^*}{a} = t^2 + \frac{b}{a}t + \frac{c}{a} \quad (2)$$

The right-hand side of (2) can be expressed as perfect square, taking its roots to be t*(twice). Thus, (2) may be rewritten as (3).

$$\frac{CR - CR^*}{a} = t^2 - 2t^*t + t^{*2} \quad (3)$$

Equation (3) was simplified to obtain (4).

$$CR = a(t - t^*)^2 + CR^* \quad (4)$$

When t = t*, CR = CR*; when t = 0, CR = at²+CR*. From Figure 1, when t = 0, CR = CR^o; thus, CR^o = at²+ CR*.

Expansion of (4), gives (5)

$$CR = at^2 - 2at^*t + at^{*2} + CR^* \quad (5)$$

Substituting three arbitrary values of t, such as t₁, t₂ and t₃ into (5) give (6), (7) and (8) respectively. From (6), (7) and (8), thickness matrix given by (9) was obtained.

$$at_1^2 - 2at^*t_1 + at^{*2} + CR^* = CR_1 \quad (6)$$

$$at_2^2 - 2at^*t_2 + at^{*2} + CR^* = CR_2 \quad (7)$$

$$at_3^2 - 2at^*t_3 + at^{*2} + CR^* = CR_3 \quad (8)$$

$$\begin{pmatrix} t_1^2 & -t_1 & 1 \\ t_2^2 & -t_2 & 1 \\ t_3^2 & -t_3 & 1 \end{pmatrix} \begin{pmatrix} a \\ 2at^* \\ at^{*2} + CR^* \end{pmatrix} = \begin{pmatrix} CR_1 \\ CR_2 \\ CR_3 \end{pmatrix} \quad (9)$$

From (3) the optimum thickness, t* was obtained as

To determine the constant a, two out of (6), (7) and (8) can be solved simultaneously. In this article, (6) and (7) were solved simultaneously, from which (11) was obtained. With known value of t*, the value of the constant, a can be calculated using (11)

$$a = \frac{CR_1 - CR_2}{(t_1^2 - t_2^2) - 2t^*(t_1 - t_2)} \quad (11)$$

The value of minimum corrosion rate, CR* can be calculated using (12), which was obtained by solving (6), (7) and (8) simultaneously.

$$CR^* = \frac{1}{3} [(CR_1 + CR_2 + CR_3) + 2at^*(t_1 + t_2 + t_3) - a(t_1^2 + t_2^2 + t_3^2) - 3at^{*2}] \quad (12)$$

From (4), when t = 0, CR = CR^o = at²+ CR*. Thus,

$$CR^o = \frac{a}{4} \left[\frac{(t_2^2 - t_3^2)(CR_1 - CR_2) - (t_1^2 - t_2^2)(CR_2 - CR_3)}{(t_2 - t_3)(CR_1 - CR_2) - (t_1 - t_2)(CR_2 - CR_3)} \right]^2 + CR^* \quad (13)$$

To investigate the authenticity of (13), the performance (durability) of coating of thicknesses below and above optimum value, together with that of optimum thickness need be estimated. It is envisaged that the graph of coating thickness against durability is also a parabola whose coordinate at turning point comprises of optimum thickness, t* and maximum durability, D*. Schematic of such graph is given as Figure 3.

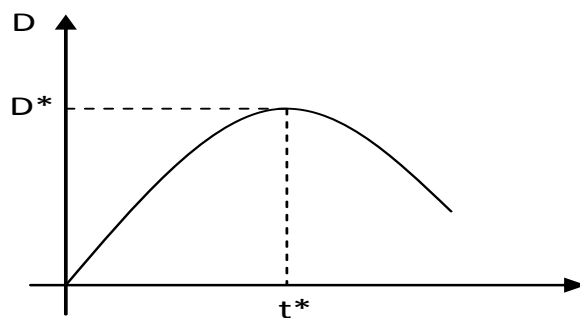


Figure 3 Schematic plot of coating thickness versus durability.

Equation of the parabola in Figure 2 is given by:

$$D = \alpha(t - t^*)^2 + D^* \quad (14)$$

When t = t*, D = D*; when t = 0, D = at²+ D* = 0, α is a constant.

Substituting three arbitrary values of t, say t₁, t₂ and t₃ into (14) give (15), (16) and (17), from which thickness matrix was obtained and given by (18).

$$\alpha t_1^2 - 2\alpha t^* t_1 + \alpha t^{*2} + D^* = D_1 \tag{15}$$

$$\alpha t_2^2 - 2\alpha t^* t_2 + \alpha t^{*2} + D^* = D_2 \tag{16}$$

$$\alpha t_3^2 - 2\alpha t^* t_3 + \alpha t^{*2} + D^* = D_3 \tag{17}$$

$$\begin{pmatrix} t_1^2 & -t_1 & 1 \\ t_2^2 & -t_2 & 1 \\ t_3^2 & -t_3 & 1 \end{pmatrix} \begin{pmatrix} \alpha \\ 2\alpha t^* \\ 0 \end{pmatrix} = \begin{pmatrix} D_1 \\ D_2 \\ D_3 \end{pmatrix} \tag{18}$$

From (18), the optimum thickness, t^* was obtained as

$$t^* = \frac{1}{2} \left[\frac{(t_2^2 - t_3^2)(D_1 - D_2) - (t_1^2 - t_2^2)(D_2 - D_3)}{(t_2 - t_3)(D_1 - D_2) - (t_1 - t_2)(D_2 - D_3)} \right] \tag{19}$$

The coefficient α , can be calculated using (20).

$$\alpha = \frac{D_1 - D_2}{(t_1^2 - t_2^2) - 2t^*(t_1 - t_2)} \tag{20}$$

The maximum durability of coating, D^* is given by

$$D^* = -\alpha t^{*2} \tag{21}$$

In an ideal case, the optimum thickness may be given as

$$t^* = \frac{1}{2} \left[\frac{(t_2^2 - t_3^2)(CR_1 - CR_2) - (t_1^2 - t_2^2)(CR_2 - CR_3)}{(t_2 - t_3)(CR_1 - CR_2) - (t_1 - t_2)(CR_2 - CR_3)} \right]$$

$$= \frac{1}{2} \left[\frac{(t_2^2 - t_3^2)(D_1 - D_2) - (t_1^2 - t_2^2)(D_2 - D_3)}{(t_2 - t_3)(D_1 - D_2) - (t_1 - t_2)(D_2 - D_3)} \right] \tag{22}$$

Also, the schematic of the combined plots of corrosion rate, durability and optimum thickness may be given as Figure 4.

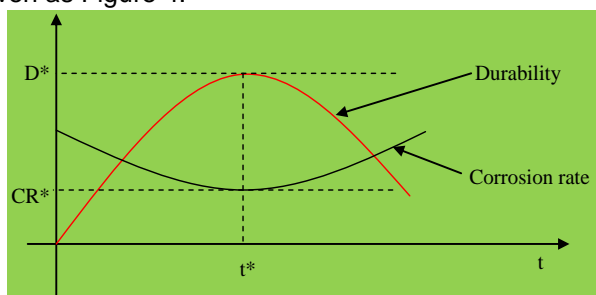


Figure 4 Typical plots of corrosion rate and durability against coating thickness

Several durability models have been proposed by different researchers. Anyanwu *et al.* [4] gave durability model for corrosion protective coating in various soil media given by:

$$t = De^{-\sigma E} \tag{23}$$

where D is durability, t is exposure time, E is corrosion inhibition efficiency, σ is a constant. Durability was given in the cited article as service life of coating measured in years. In Kovalev *et al.* [28], a model was given, which was used for predicting the durability of zinc coatings based on laboratory and field test in which the durability was also expressed as service life of coating expressed in years. Similarly, Karimbaev [29] proposed durability model for composite materials in fatigue test. In this case, durability was expressed as number of loads cycles the material can withstand prior to failure. However, the application of each model is based on objective for the application.

Maximum and minimum coating thickness

Controlling thickness of coatings during application is all importance but a challenging task due to some factors like environmental temperature, skill, humidity, available equipment, method of application, nature of Job, etc. Most of these factors are natural and difficult to manipulate. Thus, achieving exact optimum thickness is a great challenge in practical sense. Based on this, coating thickness is often taken within a given range for given coating materials and for specific jobs. Thickness range is often taken between minimum and maximum acceptable values. The impact of this practice to the service life of the coating is positive and the detail explanation has given by Kattan [30]. In addition, Baur gave the consequences of applying coatings outside recommended thickness range. In this paper, a model has been formulated as a guide for taking the appropriate maximum and minimum thickness (t_{max} and t_{min}) respectively. Looking at Figure3, it is assumed that the optimum thickness, t^* is the target thickness. Since the optimum value may not be obtained easily, a close value, say t_{min} may be taken which gives a desirable performance. The thickness, t_{min} may be located on the combined plots of durability and corrosion rate against coating thickness obtained from experimental results.

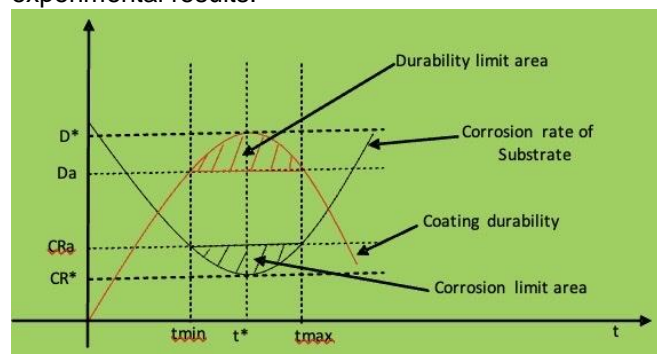


Figure 5 Schematic plots of coating performance limit diagram

The corresponding service life (durability) of t_{min} may be located on durability curve by taking a straight line from t_{min} on the thickness axis to D_a on the durability axis. It is also assumed that beyond the

optimum thickness, the maximum thickness, t_{max} is taken such that its performance is the same as that of t_{min} . Thus, between t_{min} and t_{max} , almost the same performance is achieved considering the durability of the coating and corrosion rate of the substrate. This may be illustrated diagrammatically as shown in Figure 5.

In the figure 5 $t_{min} \leq t \leq t_{max}$, $CR_a \geq CR^*$ and $Da \leq D^*$, such that CR_a is maximum acceptable corrosion rate, Da is minimum acceptable durability.

From the given illustration, coating thickness, t , may be recommended within the range (t_{min} - t_{max}). In other words, thickness, t must satisfy the condition ($t_{min} \leq t \leq t_{max}$). Society for Protective Coatings, in a specification (SSPC-2) recommended that maximum thickness be 20% above stated value and minimum thickness be 20% below stated value [31]. To apply the proposed model in accordance to SSPC-2 specification, coating thickness may be recommended in the range ($0.8t^* \leq t \leq 1.2t^*$).

Generally, the idea behind this study is that a single layer coating (especially polymer) uniformly applied over the surface of a substrate must have dry film thickness (DFT) which must fall within either of the ranges shown in Figure 6. Yellow indicates the insufficient thickness range; green indicates the optimum thickness range while red indicates the excessive thickness range. In practical sense, coating thickness should be recommended within the green range.

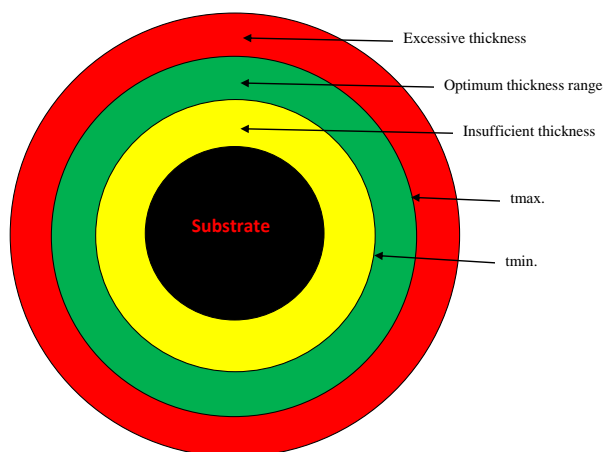


Figure 6 Proposed colour code for coating thickness.

Conclusion

From this study it may be concluded that assuming the graph of corrosion rate of coated metal against coating thickness is a parabola, the optimum thickness, minimum corrosion rate and the corrosion rate of uncoated specimen can be derived. It may also be concluded that three different thicknesses of coating on substrates of the same material and the respective corrosion rates of the coated metals must be known in order to use the proposed model for estimating the optimum thickness. The application of optimum

thickness of coating will enhance the coating performance and durability of the coated metal.

Recommendations

If the integrity of the proposed model is investigated using experimental results, the model may be recommended for industrial applications. It may also be recommended for further studies.

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Conflict of interest

The Authors has no conflicts of interest to declare that they are relevant to the content of this article.

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