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A Literature Review on the Utilization of Design of Experiments & Energy-Saving Approach in Hot-Dip Galvanization

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Abstract

This paper presents an organized review of various aspects of the hot-dip galvanization (HDG) process. For the last several decades the galvanizing industries undergo a dynamic advancement in the HDG process as well as facing two problematic issues of quality of galvanized products & excess consumption of resources. The reduction in corrosion resistance, increase in coating thickness, and microstructure & surface appearance of coating surface has been identified as a quality-related issue whereas zinc loss & increased energy consumption comes under the category of excess resource consumption. Most of the problems originated from the zinc bath kettle & the chemistry of steel products. The chemical composition of alloys, temperature & immersion time of zinc bath kettle is the 3 elements of zinc bath kettle that have a significant impact on microstructure, coating thickness & corrosion resistance of the coating. These 3 elements have dissimilar behavior on various silicon-containing steels. For the purpose to study & understand the HDG influencing factors and their effect all these 3 elements are considered carefully in this review paper. Statistical approach of design of experiments (DOE) also implemented in few research articles to solve problems of HDG process whereas energy-saving approach is also employed in HDG by using a thermodynamic approach. Considering all this, the utilization & exploration of a systematic & problem-solving statistical tool like DOE is recognized as beneficial for HDG industries to achieve efficient resource utilization with enhancement in the quality of the product.

Keywords: Hot-dip galvanization; Design of experiments; Coating thickness; energy savings; zinc consumption; corrosion resistance.

1. Introduction

Steel industries are the major unit of manufacturing industries and also have more energy demand than other manufacturing industries. The production expenses in steel industries are also very high hence protection of steel products from corrosion is necessary when they are placed in humid & corrosive environments. Steel products have a diverse application area like machinery, construction, automobile sector, power transmission, etc. Several steel products are placed in an open atmosphere like towers for high power transmission, underground piping, etc. To protect all these products galvanizing operation is performed. Hot-dip galvanization (HDG) is a common method of galvanization and is adopted by most of the galvanizing industries. In the HDG process to protect steel from corrosion a defensive coating of zinc is applied on the steel surface by dipping into molten zinc. This coating of zinc acts as a barrier between steels & the environment which prevents steels from corrosion. The corrosion resistance depends on the quality of the zinc coating. In the HDG, the corrosion resistance of the coating is linked with microstructure & the thickness of the coating [18]. The zinc consumption in the galvanization process is also increased by the excess coating thickness & dross formation into the zinc bath kettle [17]. In the HDG process, the energy losses occur from the walls & flue gases zinc bath kettle (heating furnace) [4] & [29]. The excessive consumption of resources increases production expenses which restricts the galvanizing industries to gain profit. Another reason for resource loss is due to waste products like the bad quality of coating, unnecessary over-coating of zinc layer, etc. The statistical approach of design of experiments (DOE) helps to resolve the issue like excessive coating growth in HDG and also advantageous for prediction zinc layer thickness & optimization of influencing factors [10], [27] & [30]. The statistical technique DOE screens the influencing factors and optimizes the most appropriate level of factors. Also, a statistical technique provides statistical evidence for the outcome which validates the results. DOE has various models like response surface methodology (RSM), Taguchi method & genetic algorithm, etc. that have been adopted in the galvanization process [37].

This review article describes the detailed study on the various kinds of literature based on the HDG process and corrective action adopted by the researchers to improve the HDG process.

2. Illustrations

This review section describes the 5 important research areas regarding the HDG process. The first 3 sections entail the comprehensive study on zinc bath kettle and its three essential elements alloy addition in zinc bath kettle, temperature & immersion time of zinc bath kettle. The fourth section consists of techniques used in the HDG process. Further in the fifth section research conducted regarding the energy-saving approach in the galvanization process has been discussed.

2.1. Effect of HDG bath alloy additives on thickness, microstructure & corrosion resistance of the coating

Kania, Mendala, et al. [17] studied various kinds of literature regarding hot-dip galvanizing zinc bath alloys additives, their effects on structure, morphology & thickness of the coating, and also carefully reviewed the various aspects of alloy addition. They also studied the adverse effects of alloy addition when the % composition of alloys exceeds the optimum level. The authors suggest an optimal level of various alloys. They states that the level of Aluminium (Al), Nickel (Ni), Bismuth (Bi), lead (Pb) and Tin (Sn) should be 0.005-0.01%, 0.04-0.6%, 0.05-0.1%, 0.4-0.5% & 0.1-0.3% respectively. The authors concluded that the Ni controls only the reactiveness of the Sandelin range of steels whereas Al, Sn & Bi also helps to maintain the reactivity up to some extent. The appearance of the coating surface is also enhanced by Bi, Sn & Pb addition. In this paper, the authors presented 3 optimal kinds of bath Zn-AlNiPb, Zn-AlNiBi & Zn-AlNiBiSn [17]. All these 3 baths are also selected by Kania & Komorowski [15]. The authors used these baths to test the corrosion resistance & coating thickness of specimens made from Sebisty steels (0.18% Silicon). Authors found that the least thickness obtained from Zn-AlNiBiSn bath & highest thickness gained by the bath containing pure zinc whereas the corrosion resistance of coating attained from Zn-AlNi & Zn-AlNiBiSn bath has been improved more than pure zinc bath. The bath having Pb content shows a reduction in corrosion resistance [15]. Kania & Liberski [16] has also been studied the Zn-AlNiPb bath and found that the structure of coating attained from this bath for the Sandelin range of steels is as same as the low silicon steels coating structure. The authors substantiated the claim that this bath reduces coating thickness which results in the reduction of consumption of zinc. They also concluded that the Sandelin effects are eradicated [16]. Kania, Saternus, & Kudlácek [18] have also been studied the same bath of Zn-AlNiPb and compared the corrosion resistance of coating obtained from pure zinc & Zn-AlNiPb. They used sample steel having 0.021% silicon content which comes under the category of low silicon steels. The authors reported that the corrosion resistance of the pure zinc bath is more than the bath contains Pb, Al & Ni shows. Hence it can be said that the Pb containing bath lessens the corrosion resistance property of zinc coating [18]. Kania et al. [19] experimented to study the microstructure & corrosion resistance of zinc coating obtained from Zn-AlNiBi bath for low silicon steel in hot-dip galvanization process. The authors found that the corrosion resistance of coating attained from Zn-AlNiBi is less than coating obtained from pure zinc bath. By examination of the microstructure of coating gained from Bi containing a bath, the authors found that Bi is presented at the outer surface of coating in the form of precipitates at the outer surface of the zinc coating. The Bi precipitates more prone to corrosion & form corrosion cells at the outside layer, due to which the corrosion resisting property of galvanized coating decreased [19].

Królikowska et al. [21] investigated the effect of lead (Pb) on coating obtained from the hot-dip galvanization process. They studied the behavior of pitting corrosion on the coating surface of 4 types of steel such as low silicon steel, low & high Sebisty range steels. The authors examined that the excess concentration of lead affects the longevity & authenticity of coating & its quality. Shukla et al. [14] suggested the magnesium improves the corrosion resistance when added with antimony (Sb). The authors also suggested that the Pb can be replaced by bismuth (Bi) (for environmental aspects & durability) [21]. Tang [31] reported the presence of Ni content in the galvanizing bath helps to reduce the reactiveness of less than 0.2% Si-containing steel. They also suggested that the Al addition helps to control the reactiveness [31]. Saravanan & Srikanth [25] investigated the low % of aluminum (nearly 0.11%) creates bad adherence of zinc coating surface. O. S. Bondareva & Melnikov [7] reported the bath containing nickel (Ni) suffers from excess dross formation when % Ni exceeds 0.06%.

Pistofidis et al. [24] studied the effect of Nickel & Bismuth when added together. They found that both alloys have several advantages but the Bi slightly reduces the corrosion resistance. However, the Bi also reduces the coating thickness & surface tension [24]. Fratesi et al. [11] have also been experimented to study the combined effect of Ni & Bi alloys by experimenting in 4 different hot-dips galvanizing industries. The authors investigated that when the Ni & Bi is used at 0.04% and 0.1% the reactivity of steels is controlled. They also found that the quality of phosphorous-containing steels was not good enough because of surface roughness [11]. Vourlias et al. [35] examined the effect of various zinc bath kettle alloying elements on the crystalization action & various zinc coating properties. They concluded that the outside η phase is created by Ni & Al alloys. The lead (Pb) also supports the development of the outer layer whereas tin does not affect this phase creation. The heterogeneous nucleation is tempted by copper (Cu) alloy addition [35]. The cracking phenomenon of zinc coating due to the presence of alloys such as tin (Sn), copper (Cu), and cadmium (Cd) is also studied by Katiforis [20]. Di Cocco et al. [9] substantiated the claim that the presence of copper (Cu) minimizes the thickness of the zinc layer whereas tin (Sn) increases the reactivity due to which coating thickness increases. They also claimed the Pb gives rise to the brittleness of coating structure which is absent in coating attained from the tin (Sn) containing zinc bath [9].

2.2. Effect of silicon present in steels & temperature of zinc bath kettle

An experiment is carried out by Bondareva [5] to investigate the effect of zinc bath kettle temperature. The author used a sample of nut & bolts that contains 0.22% silicon content and 4 temperature range 475℃, 485℃, 525℃ & 535℃ has been selected for the study. The author concluded that within the range of 475 to 535℃ with temperature growth the coating thickness declines. At 535℃ minimum thickness has been obtained and no phase formation has been found at this temperature as well a better coating quality such as the grey color of coating with a matte & smooth surface finish has also been attained [5]. Olga Sergeevna Bondareva et al. [8] have also been studied the behavior of temperature on the coating of steels having high silicon steel and found that at 555℃ the lowest coating thickness has been attained. Wang et al. [36] reported that at 500℃ minimum coating thickness obtained for the steel sample containing 0.102% silicon and between the 520 to 530℃ temperature range coating thickness increases parallel with temperature. Bicao et al. [3] investigated that at 480℃ highest coating thickness has been attained by a pure iron sheet having silicon less than 0.007%. Verma & Van Ooij [34] reported the maximum coating thickness has been reached at 530℃ for the steel sample that contains 0.021% silicon. Luo et al. [22] studied the behavior of dross formation and investigated that at the same temperature more dross is formed for the high silicon-containing alloy bath as compared to the low silicon-containing bath [22]. Tzimas & Papadimitriou [32] investigated for the sample steel having 0.027% silicon and found that the crack formation occurs at 560℃ temperature of zinc bath kettle which contains 99.99% pure zinc.

2.3 Effect of immersion time on the reactivity of steels

Hakim et al. [12] studied the effect of immersion time on hardness, coating thickness & microstructure in hot-dip galvanizing and found that with an increase in immersion time hardness (Rockwell hardness) decreases whereas coating thickness increases. The authors also concluded the microstructure is unaffected by varying immersion time [12]. Sepper et al. [26] investigated that the steels having silicon within the range of 0.06 to 0.11% has attained the highest coating thickness growth in comparison to other silicon-containing steels for the same immersion time. However, for 20 minutes of immersion time, each steel sample gained more coating thickness than 3.25 minutes of immersion time [26]. [17] also supported the argument of Sepper et al. (2016) and reported the steel having Si content 0.05% obtained higher coating growth than steel containing Si content 0.02%, 0.18% & 0.32%. The maximum coating thickness was obtained at 12 minutes of immersion time. Bondareva & Melnikov [6] has also been concluded that for steel 0.1% & 0.5% silicon content maximum thickness of zinc layer has been achieved.

2.4 Techniques used in HDG process

Fernandes et al. [10] used the blocking principle of experimental design to test the weight of zinc on the galvanized wire. The authors also conducted ANOVA to test the null hypothesis. Smith & Larson [28] recommended various techniques of experimental design and also solve a hypothetical example related to the galvanization process by using the full factorial experimental method. Wang [37] implemented 3 techniques of design of experiment to investigate the most influencing factor of a thickness of zinc coating. These e techniques are namely response surface methodology (RSM), Taguchi's method & genetic algorithm [37]. To predict the thickness of the zinc layer Shukla et al. [27] proposed a model of an artificial neural network. To analyze the sensitivity the Taguchi's orthogonal array technique is also utilized by the authors. Michal et al. [23] have also been adopted the design of experiments for the prediction of zinc coating thickness. Ben nasr et al. [1] utilized Doehlert design for coating thickness optimization and substantiated the claim that without changing the chemical composition of alloys present in the zinc bath the coating thickness can be minimized by optimizing temperature, withdrawal speed & dipping (immersion time). The density functional theory (DFT) is used by Jin et al. [13] The authors identified the influence of various alloys that have been added to the zinc bath. They categorized the alloys into two category effective & non-effective alloys. The authors deliberated that nickel (Ni), vanadium (V) & titanium (Ti) are effective alloys that help to minimalize the coating thickness whereas magnesium (Mg), silver (Ag) & tin (Sn) are non-effective alloys that have different uses rather than coating thickness reduction [13].

2.5 Energy-saving practices in the HDG process

Szymczyk & Kluczek [30] focused on energy efficiency & emission-free galvanization process. They examined the current state of the galvanization process, analyzed the heat balance, and prepared the thermodynamic transformation diagram for the hot-dip galvanization process line. Entropy related phenomenon is also studied by them. The authors replaced the traditional electric heater with a cogeneration system and reduced the energy consumption by up to 23%. They also argued that utilizing a cogeneration system effectively saves galvanization process energy exploitation [30]. In general electric ovens, gases like liquified petroleum gas are used to provide heat to the zinc bath kettle. Valencia et al. [33] studied the reduction in the consumption of gas in a hot-dip galvanization. The authors adopted an energy management system, investigated the indicators for energy performance, and achieved 3.2% of potential saving [33]. Sundaramoorthy et al. [29] have also been used the heat balance technique & prepared a model of "enhanced galvanizing energy profiler decision support system (E-GEPDSS)". The authors found a significant reduction in energy losses by the application of all of these techniques [29]. Bhadra et al. [2] also utilized the GEPDSS model in the galvanizing line and argued that an increase in the life of zinc bath kettle saves a substantial amount of galvanizing furnace energy.

Blakey & Beck [4] developed an equation that indicates the efficiency of a zinc bath furnace. The authors deliberated the thermal efficiency by specific energy consumption for demand & supply and concluded the all these techniques reduces the dependency on production rate for energy consumption minimization [4].

3. Analysis of literature review

From the literature survey, it is identified that there are lots of researchers who have been studied the effect of alloy addition into zinc bath kettle. They investigated the effect on corrosion resistance, coating thickness, surface appearance & microstructure of the coating. The effect of temperature & immersion time is well documented & investigated by researchers. The statistical approach of experimental design is also recognized but the number of literature regarding this field is very less as compared with research that has been conducted in the field of the chemical composition of zinc bath kettle. Studies based on energy consumption minimization in the hot-dip galvanization process have also been done by a few researchers. The graphical representation of the literature that has been studied in this paper is shown in figure 1.

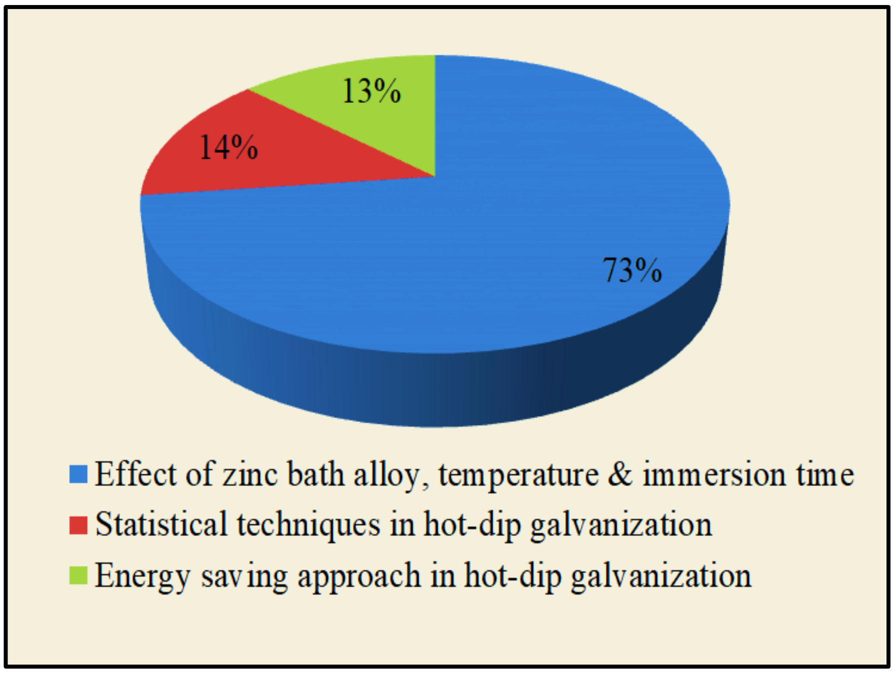

Fig. 1. Literatures studied regarding the hot-dip galvanization process

From the literature survey, essential information regarding the hot-dip galvanization process has been analyzed that are mentioned here.

1. It is found that the zinc bath kettle and its related factors have a greater influence on properties of zinc coating such as coating thickness, corrosion resistance, Rockwell hardness & microstructure of the coating.
2. The most influencing factors of zinc bath kettle are its temperature, time of immersion & chemical composition of alloys in the bath.
3. Other than the zinc bath kettle the most problematic factor is the reactiveness of the material. The reactivity is described by how much silicon is present in the material. The reactive steel has a greater influence on coating thickness.

4. In [17], the range of various types of reactive steels based on silicon % is mentioned. The authors considered the 4 types of reactive steels, low silicon steels, Sandelin steels, Sebisty steels & high silicon steels whose silicon ranges are less than 0.03%, 0.03 to 0.12%, 0.12 to 0.22% & greater than 0.22% respectively [17]. All these steels behave differently at different temperature ranges, immersion time & also according to zinc bath alloy composition. The coating thickness data on different temperature range is collected from [3], [8], [34] & [36] and comparison has been done between various silicon-containing steels.

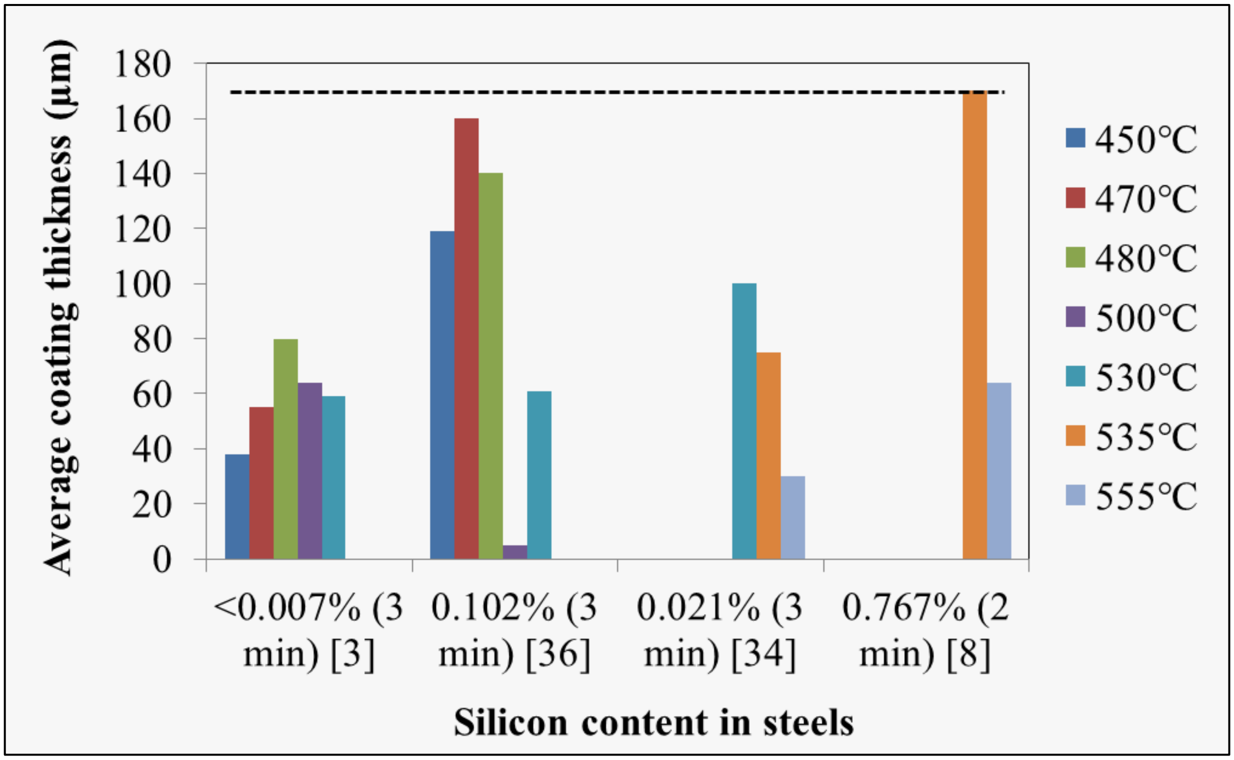

Fig. 2. Effect of temperature on zinc coating thickness for a different level of silicon present in steels

5. From figure 2 it can be viewed that for the same immersion time (3 min) for low silicon steel (0.021% Si) maximum coating obtained at 530℃ [34] whereas steels containing very low silicon <0.007% achieved maximum coating at 480℃ [3]. For Sandelin steels (0.102 % Si) maximum coating was obtained at 470℃ [36] & these steels show fluctuating coating thickness at different temperatures. The highest coating thickness was obtained at 535℃ for high silicon-containing steel (0.767%) at 2 min of immersion time [8].
6. The review of the literature [15], [17], [18] & [19] are based on zinc bath alloys which compare the coating thickness attained from different zinc baths and found that alloy composition also has equal influence on zinc coating like zinc bath temperature. A similar study is done for immersion time also in literature [12] & [26]. It is identified that for the same temperature & chemical composition of zinc bath but different coating thickness obtained with different immersion time for various kinds of reactive steels. A comparative analysis has been done for coating thickness obtained from different zinc baths [3], [15], [18] & [36] for the same temperature & immersion time for various silicon-containing steels & observed that the bath composition has a substantial effect on coating thickness of reactive steels. The coating thickness comparison graph is shown in figure 3.

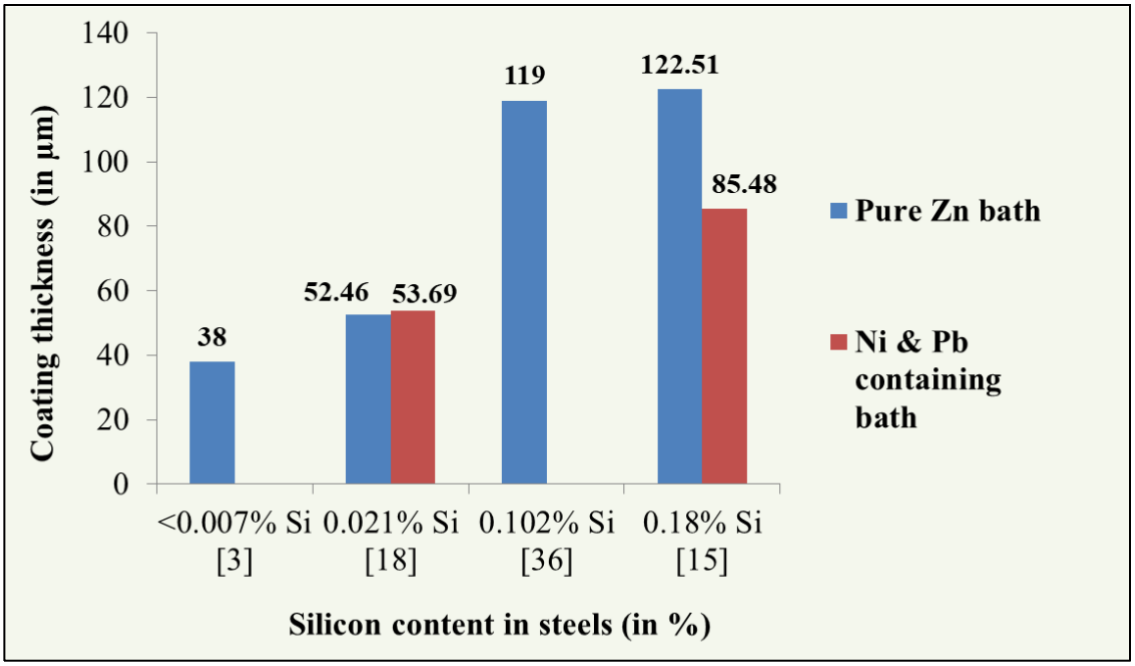

Fig. 3. Coating thickness obtained from the different galvanizing baths for various silicon-containing steels at 450°C for 3 minutes of immersion time

This analysis indicates that fixing a standard temperature, immersion time for a zinc bath kettle is not significant; both should be selected according to the chemical composition of the products & the requirement of coating thickness. It is also necessary to prepare the zinc bath alloying composition according to silicon content in products i.e. if in any galvanizing plant the more product (such as more than 75%) has a high silicon content then the alloys should be added that will control the reactivity of steels which helps to achieve optimum coating thickness.

4. Research gap & scope for future research

The works of literature based on the utilization of Design of Experiments & energy-saving have been done by a few researchers. Although many research works are related to the effect of zinc bath alloy addition, temperature effect & immersion time on various properties of galvanized products, but the lacking of statistical validation of results is identified. The utilization of experimental design in this field remains limited and also less consistent. A few studies [1], [10], [22], [23], [27], [28] & [37] taking attention to the utilization of statistical techniques like the design of experiments in the galvanizing unit to solve the problem of unnecessary thickness layer of zinc & to study the behavior of factors. Some techniques have also been adopted by the researcher to reduce energy consumption by energy management system [33], thermodynamic approach & cogeneration of heat [30], etc. but the implementation of a statistical tool such as DOE for energy consumption reduction is absent.

Future studies should explore the statistical techniques in the field of the galvanization process. The DOE gives an unbiased estimation & statistically validated results. DOE deals with experimental data, hence taking data from galvanizing industries and performing case studies delimitate the need for experimentation and will reduce the time for experimentation. Future studies could investigate the combined effect of zinc bath alloys, temperature & immersion time on various types of reactive steels by using statistical techniques such as various modules of design of experiment (DOE). In addition, the optimization of energy consumption by the implementation of the DOE tool might prove an important area for future research.

5. Conclusion

The focus of this literature review is to study the utilization of DOE tool & energy-saving approach in the HDG process by galvanizing industries as well as to understand the behavior of various factors that are related to the HDG process. Based on the literature survey following conclusions have been drawn:

- The lack of industrial data & utilization of statistical tools like DOE has been identified regarding the galvanization process. Only a few researchers used statistical tools such as DOE. Most of the literature is based on experimental results that have been performed for a particular type of steel sample and galvanizing parameters.
- The energy-saving approach in HDG is utilized by few researchers to save the energy source such as gas, electricity which is used to heat the zinc bath furnace.
- An excessive coating thickness of reactive steels, energy losses from zinc bath furnace & reduction in corrosion resistance have been recognized as the most problematic issues of the HDG process. All these 3 issues are interconnected. The thickening of coating not only consumes more energy & zinc but also increases the galvanizing cost. Also, degradation in corrosion resistance & the appearance of the coating increases the probability of product rejection by customers.
- The zinc bath alloys, immersion time, immersing temperature & percentage of silicon present in the steel sample are the major factors that have a significant influence on coating thickness as well as other properties such as corrosion resistance of coating and surface appearance of the coating.
- All of these factors have positive & negative effects on galvanizing properties which is depends upon the level of factors. The optimal level of each factor is required to improve the HDG process.
- Taking everything into account regarding the galvanization process it is found that case studies based on the utilization of statistical tools in galvanizing industries are required which helps to understand the practical implication that arises from the galvanization process.
- The utilization of statistical tools & techniques (such as DOE) provides a statistically significant & authenticated result that saves energy, helps to improve the quality of products & also profitable for the galvanizing industries.

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