



Review Article

Parameters Influencing the Hot Dip Galvanizing Processes of Sheet Metal

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Abstract: Galvanized carbon steel is one of the most used engineering material in industries, but its quality can be affected by the process parameters. The most common used galvanizing process is Hot Dip Galvanizing amongst others. The methods used were quantitative and qualitative for determining the parameters influencing galvanizing. The analytical techniques were performed by spectrometers, visual inspections thru optical and scanning electron microscope which show how parameters at the pickling, cold rolling and galvanizing processes that affect the quality of the galvanized components produced. During galvanizing there are process parameters that need to be monitored, necessitating evaluation of the process parameters that affect the hot galvanizing process. The focus of this paper is on parameters that affect the hot dip galvanizing process from different stages (pre-treatment, galvanizing and post treatment), but especially focused at the galvanizing bath. The quality of the galvanized carbon steel products gets greatly affected by the interference of the process parameters, this can lead to various types of rejects, thus influencing the quality leading to lower production output during the galvanizing process. But good follow ups of the parameters can lead to less defects which eventually increases production efficiency, component effectiveness and profit margins thus increased production of the hot dip galvanizing steels. So there is need to ensure that parameters for galvanizing are in accordance to standards.

Keywords: Galvanized Carbon Steel, Hot-Dip Galvanizing, Galvanizing, Parameters, Rejects

1. Introduction

1.1. Galvanizing

Galvanizing provides a metallic zinc envelope, which protects the carbon steel surface from corrosive action due to atmospheric and chemical influence [26]. It involves applying a thin layer of zinc coating and Aluminium to a thicker base metal, by immersing clean oxide-free iron or steel into molten zinc bath, to form a coating that is metallurgically bonded to the iron or steel surface. However this results into further reaction with carbon dioxide (CO₂) to form zinc carbonate (ZnCO₃), which protects the sheet [24, 19, 18, 8].

1.2. Properties of Galvanized Steels

Unalloyed steels can be affected by oxidation and corrosion, this results to frequent repairs and maintenance of steel products. The galvanized steel have a protective layer of zinc coating on the surface that enables sustainable use of the product, thus a significant reduction in the repair and maintenance requirement over a long period of time, resulting to both environmental and economic benefits. The process of galvanizing provides a tough metallic zinc envelope, which protects the steel surface from corrosive action due to atmospheric and chemical influence [21, 18, 26] while in use [10]. Depending on the environment, galvanized items can

last between 20 and 80 years [4, 18], a well galvanized item provided a protection to the external and internal surfaces, making them impermeable to weather or humidity [5, 4]. In comparison with other metals, the protection properties of zinc coatings is very good in sea water, industrial environment and construction [20], this has led to estimation in the increase of global steel demand growth by 1.8% [22]. Heavy coatings usually form rougher coatings than lighter coatings, because the irregularities of alloy layers tends to increase with thickness [9]. The coating formed on the steel during a galvanizing process was made entirely of zinc; however, the developments in the galvanizing processes have resulted to the current use of a mixture of Aluminium and zinc in proportions of about 55% Al and 45%Zn - as the protective coating on galvanized steels [10]. The quality of the galvanizing coat properties are achieved if the process parameters are well monitored in accordance to the procedures and standards [17].

2. Methods

The methods used are quantitative and qualitative for determining the parameters influencing galvanizing. The analytical techniques included use of spectrometers, visual inspections thru optical and scanning electron microscope to show how parameters affect the quality of the galvanized components produced.

Amazingly, galvanizing processes can be dry or wet, depending on the properties required on the final product [11], this can be by; electroplating, mechanical plating, sherardizing, painting with zinc-rich coatings, zinc plating, hot dip galvanizing, etc. [24], depending on the available technology and final requirements on the product quality. Studies show that hot dip galvanizing (HDG) has no significant changes in the mechanical properties of the structural steels, their chemical and metallurgical properties are equivalent to the uncoated steel [18, 3].

2.1. Hot Dip Galvanizing Processes

It is a process conducted in a hot state, the steel is fully immersed in a bath of zinc solution (560-630°C) and with a minimum of 98% pure molten zinc [24] which produces high quality and corrosion-resistant materials [1, 14]. The HDG process consists of the following basic steps: Surface Pre-paration (pretreatment), galvanizing, post-treatment and inspection.

2.1.1. Pretreatment/Surface Preparation

Surface Preparation is a critical initial preparation step in the galvanizing processes [8, 20]. Galvanized coatings usually fail earlier than their expected service life due to inadequate surface preparation of the item, because zinc poorly adheres to a steel surface. Each preparation step consists of either basic or acidic cleaner, this cleans the steel off the rust and dirt [4] and the preparation steps include;

degreasing, pickling, cold rolling, fluxing, galvanizing and post-treatment. Poor surface preparation of steel frustrate efforts to attain the desired property, this can be more evident in case there is interruption with process parameters. These sub processes include;

a) Degreasing / Cleaning

The quality of the product gets affected by degreasing, in this a galvanized item is dipped in a hot alkaline solution (caustic) or hydrochloric acid to remove any organic contaminants like dirt, paint, grease, oils and oxidants attached on the metal surface and then it's eventually removed [1, 14].

b) Pickling

Pickling cleans steel to be galvanized in preparation for another process. It involves immersion of steel into a bath of chemical containing either caustic (NaOH_2) or HCL or H_2SO_4 to aid the removal of scales, oxidation products and other substances like epoxies, vinyl, welding slag, etc. prior to dipping it into a rinsing tank of water [28] or alcohol [4].

c) Cold Rolling Mill (CRM)

In a cold rolling process, the Hot Rolled Coil (HRC) sheet from pickling process passes in between rollers, rolling in opposite direction, reducing the sheet to a particular thickness without application of heat. The sheet is then trimmed at the sides to remove any dents from the sheet and to give the sheet a specific required width, after which it's then coiled in preparation for the next process.

d) Fluxing

Fluxing is done after degreasing, pickling and sometimes cold rolled prior to dipping the steel into the galvanizing bath containing molten zinc and Aluminium [5, 10]. However this takes a few minutes depending on the technology used. It is done to prevent further oxidation of the metal [6].

2.1.2. Galvanizing Bath

After fluxing, the metal (steel) is fully immersed in a bath of temperature of about (445 – 465)°C or 850°F and with a minimum of 98% pure molten zinc. However, further reaction with carbon dioxide (CO_2) collected from the atmosphere where its sub stored, forms zinc carbonate (ZnCO_3), [24, 19, 8] which protects the sheet. During the process of galvanizing, the dipping of the steel material takes place at the different processes as seen in a summary of the major steps in hot dip galvanizing line as illustrated in Figure 1.

2.1.3. Post-treatment / Inspection

In this, it involves monitoring of the quality standards on the galvanized items. It depends on the process quality requirement [8] for a given product, in accordance to established, well-accepted and approved standards [5]. The properties are scrutinized by physical visual inspection and laboratory tests to determine coating thickness, uniformity, adherence and appearance.

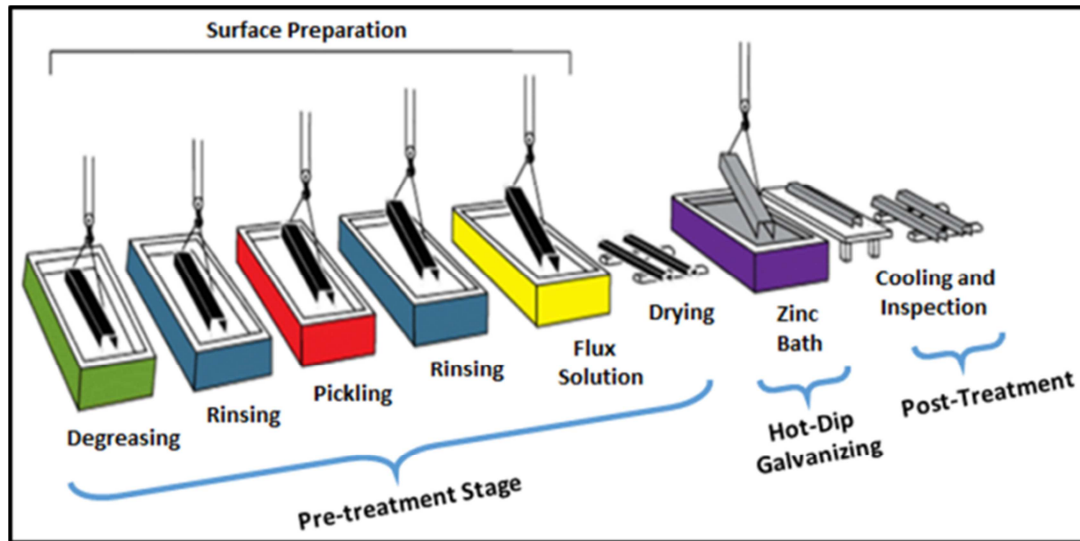


Figure 1. Different processes in Hot Dip Galvanizing [6].

2.2. Types of Galvanizing Processes [3]

There are different methods of Protecting steel with Zinc namely; electroplating, sherardizing, mechanical plating, painting with zinc-rich coatings, Hot Dip Galvanizing, galvanizing sheeting and zinc plating [20], [3].

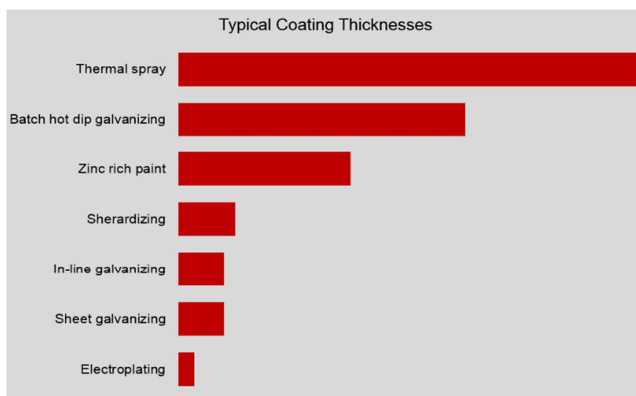


Figure 2. Shows the typical relative thickness of each coating.

Electroplating; Is an economic, versatile and effective method of applying a protective zinc coating to small steel components.

Mechanical plating; In this the coating thickness is often similar to that of electroplated items

Continuous galvanizing processes (in-line galvanizing); The articles always produced have thinner coatings than batch hot dip galvanizing for the same steel thickness and therefore offer less corrosion protection when exposed to the same environment.

Sherardizing and thermal diffusion; This involves heating steel articles in a closed rotating drum that contains metallic zinc dust approximately 500°C. At temperatures above 300°C, zinc evaporates and diffuses into the steel substrate forming diffusion bonded Zn-Fe-phases. Sherardizing and thermal diffusion are most effective for small articles. Its coating

thickness varies from 20 to 120 μm .

Zinc rich paints; Here coatings are made of metallic zinc dust in organic or inorganic binders, coatings can be applied by brush or spray.

Thermal spray (or metalizing); This is done by spraying semi-molten zinc, other metals alloys onto fabricated items using wire or powder heated by a flame, arc spray or plasma heat source. It zinc coats up to 250 μm thick. It's more expensive than batch hot dip galvanizing for the equivalent section.

3. Results and Discussions

Parameters influencing Hot Dip Galvanizing Process

During production of a galvanized item (sheet), there are processes the item passes through, before its dispatched to the market or to other post galvanizing processes like color coating and all these have parameters that require monitoring, of which these include;

3.1. Pickling

Once deliverance of Hot Rolled Coil (HRC) coils for processing is done, they are cleaned by dipping the steel in an acid in a pickling bath and then the acid is rinsed off with water, to prepare the HRC for the further processes. The parameters that affect the pickling process are seen from table 1. The pickling process, if not well handled can lead to under or over pickling [28] as shown from figure 3;

i. Over pickling

Results show that, some acid remains on the surface of the sheet resulting to pitting effect or over pickled surface, thus excess zinc consumption at the galvanizing bath leading to an increase in coating weight and this also accelerates attack of molten zinc on the steel surface [15] increased chemical consumption and wastage of material.

ii. Under pickling

Also its seen that when there is interruption of the process parameter, the sheet is not fully cleaned or when weak acid

concentrations is used or higher content of iron salts is in the pickling bath, this results into black spots [27], more sludge formation during galvanizing. Good quality of pickling can be

achieved when the iron salts are normal, parameters of pickling remains in the range between Hydrochloric acid concentration 8 -10% in the pickling bath.

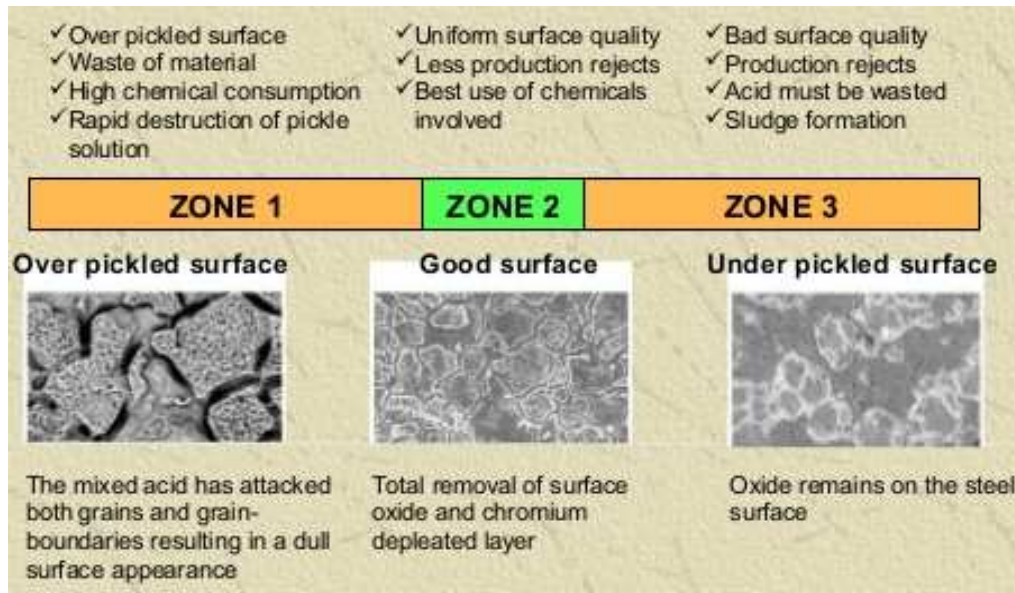


Figure 3. Comparison of surface finish during pickling process.

Table 1. Parameters Influencing Pickling Process.

No.	Parameters	Expected range	Operation Level	Remarks/ Purpose	Parameter Interruption	Effect(s)
1	HCL Concentration %	10-20	17	It fluctuates depending on the condition of HRC.	Some droplets can remain on the sheet	Causes pitting
2	HRC delivered with Fe ₂ O ₃ , 2FeO (rust) (%)	95-99	96-97	Depends on the condition of weather during transportation	Not effective cleaning is realized	Under pickling
3	Inhibitors	-	-	To prevent any acid to remain onto the sheet	Their absence affects quality	Over pickling
4	Sheet thickness (mm)	1.8-2.5	Proportional to speed of the line and rolls ref. figure 4.	Thin sheets use high speed for effective cleaning thus grade	For thin sheets changes on the speed;	High and Slow speed results to Sheet tear and over pickling respectively
5	Flow rate of the acid (litres/hour)	420-1000	750	Depends on sheet thickness, amount of dirt and pressure on the acid	Low rate, with less pressure can	Results to under pickling
6	Pressure of acid (bars)	3-6.5	5.5	To cause the acid turbulence	Pressure drops	Results to under pickling
7	Pressure of water (bars).	2.5-4.0.	3.0	Pressure of water to cause turbulence during rinsing	Pressure drops pitting of the acid on to the sheet	Results to no effective rinsing

During pickling with HCL, the component (item) to be cleaned is dipped in a dilute solution of hydrochloric acid, of 10% - 20% concentration, with optimum concentration level of (15%) at 25°C, then rinsed with water [28]. The process takes about 30 to 90 minutes, depending on the complexity of the item, the thickness of the material, the degree of contamination of the item being made for the chemical being used and the line speed. During pickling, the chemicals are usually used together with inhibitors. The inhibitors prevent acid from reacting with the sheet and the squeezer rolls remove any acid concentration left on the sheet. Poor pickling procedures may fail to or over remove the adherent iron salts on the material, leading to defective products (*Under-pickling and Over-Pickling*) respectively [28]. The properly pickled sheet may or may not be rolled to a required thickness and width, depending on the product requirements,

then the pickled item is ready for the next process.

3.2. Process Parameters Influencing Cold Rolling Mill

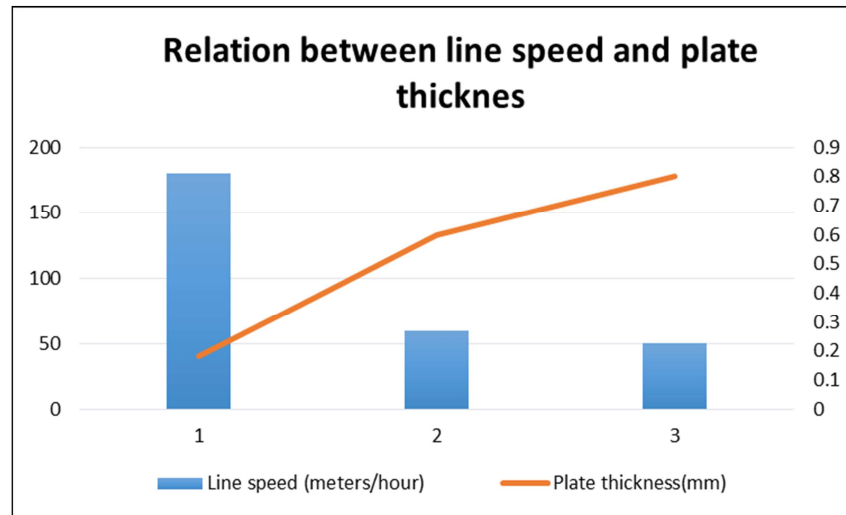
It was observed that, cold rolling machine parameters like; roller clearance settings, gear meshing once interfered, especially when a roller seizer occurs because of the damaged bearings affect the process. The line speeds do affect the quality of the sheet to be rolled [2]. The trends on figure 4. in reference to data from table 3, these show that line speed is greatly dependent on the plate thickness during rolling, example smaller plate thickness require lower line speeds. It's seen that, the cooling water temperature parameter, increases when the chiller units get switched off thus influencing the process quality. Here is table 2, which shows a summary of parameters that interrupt cold rolling process

Table 2. Parameters influencing the Cold Rolling Milling.

No.	Parameters	Expected range	Operation Level	Remarks/Purpose
1	Roll speed (meters/hour)	300 - 800	500	Dependent on the thickness of the sheet, thinner gauges usually use increased speed.
2	Line speed (rpm)	500-1800	1200	Line speed is dependent on the thickness of the sheet
3	Number of rolls	6 rolls	Dependent	It is dependent on the thickness/ gauge being processed. More rolls are used for thicker gauge.

Table 3. Line speeds in relation to plate thickness during rolling.

Line speed (meters/hour)	Plate thickness (mm)
180	0.18
60	0.60
50	0.80

**Figure 4.** Comparison of line speed and plate thickness during rolling

3.3. Fluxing

Fluxing is done prior to dipping the steel into the galvanizing bath, it involves passing the surface of the cleaned item (sheet) through an alkali spray (caustic of 4 – 5% concentration), then rinsed with hot water (60°C), before its air dried (100°C), then finally air cooled (30-40°C), then the sheet is passed through the furnace for heat treatment process, depending on the desired property on the sheet, before it is immersed in to the zinc pot (galvanizing bath), any interference on this affects the quality of fluxing and galvanizing.

Fluxing can be dry or wet, depending on the galvanizing process used. In wet fluxing, the sheets are fluxed in hot zinc ammonium chloride solution at about (65-80)°C to aid the wetting and the reaction between the molten zinc and the steel. The aqueous flux solution deteriorates by dilution and becomes weaker [14]. The dipped or pre-fluxed of 30% zinc ammonium chloride with wetting agents, the material is then air dried (50°C) ready for galvanizing.

3.4. Galvanizing

Hot Dip Galvanizing (HDG) is the process most widely used for a long period in the galvanizing on steel. It is conducted in a hot state, by dipping a metal in a hot bath of zinc solution (560-630°C), which produces high quality and corrosion-resistant materials [1, 14]. The properties that are

scrutinized by physical visual inspection and laboratory tests to determine coating thickness, uniformity, adherence and appearance because change in process parameters affect.

3.4.1. Parameters Influencing the Hot Dip Galvanizing Process

The hot dip galvanizing process is the most widely used method for galvanizing steel materials, usually conducted in a hot state, by dipping an item in a hot bath (560-630°C) of zinc solution. The operating parameters that affect the quality of galvanizing [17] and the galvanized product include: drying temperature, dipping techniques, withdrawal speeds, Zinc bath additives, Aluminium content, the size of the kettle (bath), composition of the steel and the furnace pressure [1], these are discussed below but the specifics are to a particular galvanizing line capacity;

i. Drying Temperature

The optimum drying temperature at 250 – 300°C prior to the metal entering the bath (fluxing process). Good fluxing results to better quality products. High drying temperature causes black spots (burned flux) and too low a drying temperature leads to the appearance of uncoated areas [1]. The Temperature control of the galvanizing bath, heating zones, furnaces (hot dry air, hot water, oxidizing zone) get interrupted when there is any power interruption, because these parameters require continuous control and monitoring. The galvanizing bath temperatures, gets interfered resulting to

development of high stresses at the interface of the steel, due to difference in expansion or contraction of the steel [23, 20] this affects the material properties, therefore calls for high control of process parameters.

ii. Dipping techniques

The dipping technique used has much influence on the structure and coating thickness on the item being galvanized. After surface pretreatment, the dried sheets are dipped in the molten zinc bath for a short time (less than 1 min) and then withdrawn. A fully immersed item gets better coated than the sprayed items.

iii. Effect of bath temperatures and withdrawal speeds

The galvanizing bath temperature and withdrawal speed affect the alloy layer thickness of a galvanized item [2, 1]. High withdrawal speed of the material can result in defects like bare spots and the delayed withdrawal of the material can result in defects like grey coatings, curtain formation, tears, peeling, flaking, etc., this necessitates control of temperature and withdrawal speeds of which this requires steady supply of power, so there is need to correlate between the temperature of the zinc bath and the withdrawal speed for a given metal thickness.

iv. Steel sheet thickness

Sheet thickness has an effect on quality of the coating. The thickness layer depends on the material thickness [2, 16], this affects up to 1.5mm material thickness by 45 microns. When the surface cleanliness of cold rolled sheet is poorer, the oil and residual iron can remain on the sheet surface, this increases with increasing sheet thickness [25], thus requiring further cleaning of the sheet after the rolling process.

v. The Zinc bath additives

The mode and amount of additives into the galvanizing bath greatly influence on the product quality. Aluminium and antimony are the most common metals added to the zinc bath to improve the quality of the coatings and this should be added in required proportions. The amounts of catalysts like titanium is used to catalyze iron-Aluminium reaction, to allow better inhibition of the substrate layer and delaying the growth of Fe-Zn intermetallic [20].

vi. The Aluminium content

The Aluminium content in the galvanizing bath do affect the coating structure and the properties of the galvanized steel item. The Aluminium content should be between 5 - 90% [13] and this always be controlled to maintain quality standards, failure can lead to rejects.

vii. The Immersion time

Results show that, a parameter like immersion time in the galvanizing bath varies from a few minutes for light articles, to several minutes for relatively heavy articles, up to half an hour or longer for major structural members [19], but this depends on the thickness (size) of the item being galvanized [2] and the chemical composition of bath. The bath soaking time should be long enough to promote the isothermal transformation of austenite into a fine pearlitic microstructure [21, 20]. Interruption of parameters like this can lead to defects like outbursts, flaking's, etc. [12].

viii. The Size of the kettle

The size of the galvanizing bath or pot or kettle has an

influence on the components to be galvanized. Galvanized items need to be submerged fully in the hot zinc solution. Very long items will require double dipping, which is associated with some defects (visible indentation of two dips overlap) [19].

ix. The Composition of the steel

The steel composition is key, because the amount of other constituent elements in the steel should be to the required limits. For example C in excess of 0.25%, Si 0.04% - 0.22%, may result to a galvanized coating having a duller or matt gray appearance, or a blotchy variable appearance, P in excess of 0.04%, Mn excess of 1.3%; as this can affect the quality of the galvanized material [18, 15, 20].

x. Good design

Good design of the galvanizing process line has a key impact on the end products; there should be good ventilations and drainage holes to permit free circulation of the air. The surface preparation area should allow passage of fluids like acid, water, etc. and zinc to all cavities, to ensure full coverage of a galvanized component. The zinc should travel freely (turbulence) in the galvanizing bath [19].

xi. The flow of Hydrogen and Oxygen

Hydrogen flow influences the formation of oxides on the surface of the sheet; that is, its circulation ($75 \text{ NM}^3/\text{Hr.}$). Hydrogen should be monitored, due to oxidation as a result of the steel reacting with hydrogen and oxygen molecules. Oxygen flow at the oven should be maintained as low as possible (-32 to -50 ppm), because it can lead to peeling or flaking of the galvanized sheet coating. If this is not well monitored can affects quality of the product.

xii. The Furnace pressure (324 Pa) and Exhaust pressure (-300 to -400 Pa)

However, if the pressures are not well monitored, this results to defects like outbursts, flaking's, distortions and blast damage due to pressure fluctuations. In order to maintain the quality of the galvanized sheet, these pressures and temperature have to be monitored, this helps to control the flue gasses which can affect the quality of the sheet. However it's observed that, parameter like pressures (galvanizing bath, furnaces, exhaust), need no interferences, these affects preparations of the material and adhesion of zinc Aluminium into the item being galvanized.

xiii. The humidity of the Chromating area

The humidity of the Chromating area affects the adhere-ration of the Zinc Aluminium onto the sheet. The humidity has to be between 15 - 16% for effective results. Very little humidity can result in peeling off effect and high humidity can result in excess coatings.

xiv. The flow rates

Furthermore, the flow rates of parameters like Hydrogen content / Percentage ($75 \text{ NM}^3/\text{hour}$), Nitrogen content /percentage ($300 \text{ NM}^3/\text{hour}$), Oxygen content / Percentage (-32 to -50PPM) and Dew point related to oxygen (- 50 to + 50 PPM). The flow rates of the different fluids if altered or interrupted affects processes which eventually leads to rejects. Other parameters that govern the galvanizing process are mentioned in the table 4;

Table 3. Parameters influencing the galvanizing process.

No	Parameters	Expected range	Reasons / purpose	Effect of parameter interruption
1	Galvanizing pot (bath) composition elements %	54-55 Aluminium, 43-44 Zinc, 1.6 Silicon and other trace elements	Should be within range to reduce defects.	Alloying elements, interference of the adhesion of the elements
2	Alkali – caustic	4 - 5%	Sprayed to reclean the sheet for any further oxidation that could have happened before it enters the galvanizing area.	Poor adherence thus reduce life by a factor of steel [5]
3	Hot water (°C)	40 -70	Water is sprayed to flash off any caustic effect on the sheet.	Water cools down so delay drying time
4	Hot dry clean air at (°C)	80 -150	To dry air before the sheet is passed into the air coolers. The presence of steam, fumes, exhaust gases, dust and grit are detrimental next processes.	Air cooling and dryness factor lowered, thus influencing the adhesion of the Zinc-Allumin
5	Furnace temperature (°C)	900 – 1100	But this depends on the thickness of the material (sheet)	If lowered below expectation and some areas get overheated
6	Radiant due furnace (RDF) zone (°C)	700	Is activated only when annealing the sheet e.g. for color coating	Affects sheet annealing
7	Jet cooling set (JCS) zone (°C)	550	Cools the sheet ready for galvanizing (seed).	Affects cooling down
8	The condition of the rollers.	Shouldn't be damaged	Presses and guides the sheet	Roller gets seizure effect, misaligned
9	Chromating the galvanized sheet, (°C),	Air cooled (60 - 65), hot water tank (100 - 110), hot air compressed, humidity of the area (15 -17%).	Cleans, dries the sheet to prepare it for Chromating. Dependent on the sheet thickness.	Affects coating thickness and surface finish
10	Brush scrapper,	Brush bristles should be longer <1"	To clean off any foreign material from entering the heating furnace zones.	Bristles clog thus less cleaning impact

3.4.2. The Defects in a Galvanized Steel Products and the Influencing Variables

Quality Aspects in Hot Dip Galvanizing processes of steel products requires inspection to ensure compliance to required standards and these requires a clear understanding of specification requirements and compliance measurement techniques to make an accurate assessment [6]. Failure to meet the set quality standards can lead to rejects and these are; Poor Surface Finish, Blasting Damage, Clogged Holes, Delamination, Dross Inclusions, Excess Aluminum in Galvanizing Bath, Flux Inclusions, Zinc Skimmings, Zinc Spatter, Runs, Rust Bleeding, Striations/Fish-Boning, Surface Contaminant, Weeping Weld, Welding Spatter, Wet Storage Stain, Welding Blowouts, Bare Spots, Drainage Spikes, Clogged Threads, Oxide Lines, Rough Surface Condition, Distortion, Flaking, extra.

3.5. Pos-treatment / Inspection

The post-treatment steps that influence the coating quality are: the cooling air distribution, the degree of cleanness of the withdrawing rollers, the passivation step before storage. These steps are necessary to prove the compliance of the product [6]. Poor adherence to quality parameters during surface preparation (pretreatment) [25], galvanizing procedures and post treatment can lead to production of poor quality products, which then will lead to rejection of the final product.

4. Conclusions

In order to obtain high quality galvanized carbon steel, it is important to ensure that parameters for galvanizing follow

specified procedures, standards and continuous monitoring of process parameters that influence the galvanizing process and it's critical at the galvanizing area. These affects the quality of galvanized carbon steel in a galvanizing process which eventually affects the manufacturing process output. But good follow ups of the parameters can lead to less defects which eventually increases production efficiency, component effectiveness and profit margins thus increased production of the hot dip galvanized steels.

The parameter changes that affect the galvanizing process are due to changes in; flow rates, pressures (pickling and galvanizing bath, oven exhaust, furnaces), the chemistry and management of temperatures (pickling bath, fluxing, coolers of cold rolling mill, galvanizing bath, oven), the condition of the dross in the galvanizing pot, the line speeds, the dipping techniques used, the type of galvanizing processes - post-treatment on the product. Also what affects quality and production are; the concentrations / percentage of hydrogen, nitrogen, and oxygen content, this results to rejects thus reduced average production efficiencies, leading to increased production costs due to additional costs of production (directly or indirectly).

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Conflicts of Interest

All the authors do not have any possible conflicts of interest.

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