

ACID ZINC PLATING FOR AUTOMOTIVE PARTS-REDUCTION OF COST AND CYCLE TIME

Submitted in partial fulfilment of the requirements for the award of
Bachelor of Technology degree in
CHEMICAL ENGINEERING

By

A.MANIKANDAN(39690007)

C.PALANISAMY(39690009)



**DEPARTMENT OF CHEMICAL ENGINEERING
SCHOOL OF BIO-CHEMICAL ENGINEERING**

SATHYABAMA

INSTITUTE OF SCIENCE AND TECHNOLOGY
(DEEMED TO BE UNIVERSITY)

Accredited with Grade “A” by NAAC

JEPPIAAR NAGAR, RAJIV GANDHI SALAI, CHENNAI - 600 119

NOVEMBER - 2022



SATHYABAMA

INSTITUTE OF SCIENCE AND TECHNOLOGY

(DEEMED TO BE UNIVERSITY)

Accredited "A" Grade by NAAC | 12B Status by UGC | Approved by AICTE

www.sathyabama.ac.in

DEPARTMENT OF CHEMICAL ENGINEERING

BONAFIDE CERTIFICATE

This is to certify that this Project Report is the Bonafide work of **A. MANIKANDAN (39690007), C. PALANISAMY (39690009)** who carried out the project entitled **"ACID ZINC PLATING FOR AUTOMOTIVE PARTS-REDUCTION OF COST AND CYCLE TIME"** Under our supervision from July 2022 to October 2022.

Internal Guide

Dr.D. PRABU, M.S (BY RESEARCH), Ph. D

Associate Professor

Head of the Department

Dr.S. SATHISH, M.E, Ph. D

Associate Professor

HEAD OF THE DEPARTMENT
DEPARTMENT OF CHEMICAL ENGINEERING
SATHYABAMA
INSTITUTE OF SCIENCE AND TECHNOLOGY
(DEEMED TO BE UNIVERSITY)
Jeppiaar Nagar, Rajiv Gandhi Salai,
Chennai - 600 119

Submitted for Viva voce Examination held on _____

Internal Examiner

External Examiner

DECLARATION

We, **A. MANIKANDAN (39690007)** and **C. PALANISAMY (39690009)**, hereby declare that the project report entitled “**ACID ZINC PLATING FOR AUTOMOTIVE PARTS-REDUCTION OF COST AND CYCLE TIME**” done by us under the guidance of **Dr.D.PRABU**, M.S (By Research), Ph.D., Associate Professor, Department of Chemical engineering, Sathyabama Institute of Science and Technology is submitted in partial fulfilment of the requirements for the award of Bachelor of Technology degree in Chemical Engineering.

DATE :

PLACE:

SIGNATURE OF THE CANDIDATE

1. A. MANIKANDAN

2. C.PALANISAMY

ACKNOWLEDGEMENT

We are pleased to acknowledge my sincere thanks to Board of Management of SATHYABAMA for their kind encouragement in doing this project and for completing it successfully. I am grateful to them.

We convey our thanks **Dr.S.SATHISH**.ME, Ph. D, Head of the Department of Chemical Engineering for providing us necessary support and details at the right time the progressive reviews.

We would like to express our sincere and deep sense of gratitude to my project guide **Dr.D. PRABU**, M.S (By Research), Ph. D for this valuable guidance, suggestions and constant encouragement paved way for the successful completion of my project work.

We wish to express our thanks to all Teaching and Non-Teaching staff members of the Department of Chemical Engineering who were helpful in many ways for the completion of the project.

A. MANIKANDAN

C.PALANISAMY

ABSTRACT

A review of sacrificial Zn electroplating coatings on high -strength steels is presented. These steels are used for heavy structural applications such as brakes assemble, that are subjected to high stresses and corrosive environment in service. The electroplating process involving aqueous electrolytes invariably produces hydrogen. The emitted hydrogen can diffuse into substrate steel, contributing to the delayed failures by hydrogen embrittlement. Microstructural inhomogeneities arising from the heat treatments and defects produced during coatings and those inherently present in the steels can trap hydrogen emitted during plating. Dissolved and trapped hydrogen can slowly diffuse to the stress concentrations or crack tips, contributing to the delayed structural failures. Baking after plating helps to eliminate hydrogen to some extent, though it may introduce some thermomechanical stresses at the biomaterial interfaces. EUROPE, USA, MEXICO, ASIA Automotive Industry's currently doing acid zinc plating with single step process sequence. Indian Automotive Industry's currently doing acid zinc plating with two step process sequence. Indian Automotive Industry's acid zinc plating with single step process sequence not yet implement in India. We have currently trial conduct at bright electro process for acid zinc plating with single step process sequence.

Keywords: electroplating; high strength steels; hydrogen embrittlement; Zn coatings

TABLE OF CONTENTS

CHAPTER NO	TITLE	PAGE NO
	ABSTRACT	i
	TABLE OF CONTENTS	ii
	LIST OF TABLES	v
	LIST OF FIGURES	vi
	LIST OF ABBREVIATIONS	vii
1	INTRODUCTION	1
	1.1 ELECTROPLATING OF ZINC	2
	1.2 SELECTION OF ZINC COATINGS	3
	1.3 THE BENEFITS OF ZINC ELECTROPLATING	3
	1.4 COATING THICKNESS VS. COATING WEIGHT	5
	1.5 PROBLEM STATEMENT	6
2	LITERATURE SURVEY	
	2.1 LITERATURE 1	7
	2.2 LITERATURE 2	7
	2.3 LITERATURE 3	8
	2.4 LITERATURE 4	8
	2.5 LITERATURE 5	8
3	AIM & SCOPE OF ACID ZINC ELECTROPLATING.	9

CHAPTER NO	TITLE	PAGE NO
4.	MATERIALS AND METHODOLOGY	10
4.1	DESIGN OF COMPONENT FOR ELECTROPLATING PLANT	10
4.1.1	<i>Electroplating bath tank</i>	10
4.1.2	<i>Electrode</i>	11
4.1.3	<i>Power supply</i>	11
4.2	PROCESS SEQUENCE FOR ELECTRO PLATING	12
4.2.1	<i>Degreasing</i>	12
4.2.2	<i>Rinsing water</i>	12
4.2.3	<i>Acid pickling</i>	12
4.2.4	<i>Passivation</i>	12
4.2.5	<i>Top coat</i>	13
4.3	EXPERIMENTAL STUDY OF ACID ZINC ELECTROPLATING	13
4.3.1	<i>Previous Automatic Acid Zinc Plating Process Sequence 1</i>	13
4.3.2	<i>Current Automatic Acid Zinc Plating Process Sequence</i>	14
4.3.2	<i>Hydrogen Embrittlement and Electroplating</i>	18
4.3.3	<i>What Is Hydrogen Embrittlement</i>	18
4.3.4	<i>How To Prevent Hydrogen Embrittlement</i>	18
4.3.5	<i>Post Plating Baking</i>	18
4.3.6	<i>Adding Inhibitors during Pickling</i>	19
4.3.7	<i>Substituting Metal Alloys</i>	19

5.	PERFORMANCE ANALYSIS	20
	5.1 PROCESS SPECIFICATION	20
	5.2 PROCESS COST COMPARISON OF PREVIOUS V/S CURRENT	21
6.	RESULTS AND DISCUSSION	23
	6.1 ELECTROPLATING FINAL PRODUCT FINISH	23
	6.2 COATING THICKNESS REPORT STRUT	26
	6.3 COATING THICKNESS REPORT SCREW	27
	6.4 PLATING ADHESION TEST REPORT STRUT	28
	6.5 PLATING ADHESION TEST REPORT SCREW	30
	6.6 SALT SPRAY TEST REPORT STRUT	32
	6.7 SALT SPRAY TEST REPORT SCREW	33
7.	CONCLUSIONS	34
	REFERENCES	35

LIST OF TABLES

NO	TITLE	PAGE NO
1.1	The coating densities, in terms of thickness required to equal 1 oz. of zinc per square foot of surface	4
1.2	The coating densities, in terms of thickness required to equal 1 oz of zinc per square foot of surface	5
5.1	Passivation and Sealer Parameter Details	20
5.2	Process Cycle Time Comparison of Previous vs Current	20
5.3	Production Yield Comparison of Previous vs Current	21
5.4	Previous Process Cost Details	21
5.5	Current Process Cost Details	22
5.6	Manpower Cost Comparison of Previous vs Current	22

LIST OF FIGURES

FIGURE NO	TITLE	PAGE NO
4.1	Electroplating Bath Box	10
4.2	220v primary 12v secondary step-down transformer	11
4.3	Step 1 Acid Zinc Plating Process Sequence	15
4.4	Step 2 Acid Zinc Plating Process Sequence	16
4.5	Single Step Acid Zinc Plating Process Sequence	17
6.1	Before Oven Finish for Strut	23
6.2	After Oven Finish for Strut	23
6.3	Final Finish for Strut	24
6.4	Before Oven Finish for Screw	24
6.5	After Oven Finish for Screw	25
6.6	Final Finish for Screw	25

LIST OF ABBEREVATIONS

ABBEREVATIONS	DESCRIPTIONS
°C	Celsius
°F	Fahrenheit
SEM	Scanning electron microscope
PVD	Physical vapor deposition
HD	Hydrogen de embrittlement
HCL	Hydrochloric Acid
ML	Milli litter
LIT	Litter
SEC	Second
V/S	Versus
sq.ft	Square feet
gm	Grams
sq.inch	Square inch
RS	Rupees
Cr3+	Trivalent Chrome
µm	Microns
XRF	X-ray fluorescence
H ₂ O	Water
WR	White Rust
RR	Red Rust
Psi	Pressure

CHAPTER - 1

1 INTRODUCTION

Electroplating is an electrode position process for producing a dense, uniform, and adherent coating, usually of metal or alloys, upon a surface by the act of electric current. The coating produced is usually for decorative or protective purposes, or enhancing specific properties of the surface. The surface can be conductors, such as metal, or non-conductors, such as plastics. Electroplating products are widely used for many industries, such as automobile, ship, air space, machinery, electronics, jewellery, defence, and toy industries. The core part of the electroplating process is the electrolytic cell (electroplating unit). In the electrolytic cell (electroplating unit) a current is passed through a bath containing electrolyte, the anode, and the cathode. In industrial production, pre-treatment and post treatment steps are usually needed as well.

Electroplating is widely used for production of new materials that require specific mechanical, chemical and physical properties. This technique has demonstrated to be very convenient because of its simplicity and low cost in comparison with the other method such as sputtering and vapor deposition. Pure tin is non-toxic, can be electrodeposited as an extremely bright, white and lustrous deposit. It has excellent resistance to corrosion and easily to be soldered. As mentioned previously, it is being applied to produce tin cans for food packaging. However, pure tin is soft and is not practical to be used as coated material for automotive applications. While the hardness of alloys coatings such as White Mir alloy (55%Cu-45%Sn or 55%Cu-30%Sn-15%Zn) and Yellow Mir alloy (80%Cu-17.5%Sn-2.5%Zn, 80%Cu- 15%Sn-5%Zn or 85%Cu-15%Sn) are respectively 550 HV and 400 HV. These coating layers are extremely abrasion resistant and are suitable for automotive application. The coatings also exhibit other interesting characteristics such as low surface tension, good sliding ability, high hardness, sufficient ductility; solder ability, low porosity and/or resistance to corrosion depending on their composition. Such properties have led to these coating being widely used in industries. For example, because of White Mir alloys exhibit an acceptable contact resistance, it may be used for coating electric connectors. Moreover, worn machine parts can be re-electroplated by these alloys to extend their service life. These may lead to a decrease in the cost of the parts. Recently, it has been

reported that electroplating of Cu-Sn alloys can be successfully done in laboratories using non cyanide solution e.g. in acid sulfate solution. Even though co-deposition of such alloys can be done using non cyanide baths, most of the industrial tin alloys plating use cyanide solutions because of the high-quality requirement of the coating. Electrode position in cyanide bath will produced adherent, smooth and uniform coating on both planar and non-planar substrates. Moreover, quaternary alloys (e.g., an alloy which contains Cu 50 %wt., Sn 32 %wt., Zn 17 %wt. and Ni1%wt) can be easily electrode posited from cyanide baths. Cyanide is deemed typical of completing agents that have been used for long time in providing stable solution. It is still used intensively in industries such as in gold extraction plants and in electroplating industries

1.1 ELECTROPLATING OF ZINC

Electroplated zinc protects steel, cast iron, malleable iron, copper, and brass from destructive corrosion. The zinc chemically bonds to the part surface and functions as a "sacrificial coating", corroding before the base material but in the process greatly extending part life. To increase the corrosion protection Chem Processing Inc. offers RoHS compliant clear trivalent chromium and yellow trivalent chromium seals, as well as yellow dichromate and olive drab hexavalent chrome-based seals. Chemo Processing, Inc. also offers a range of inorganic and organic topcoats; such as Doer kenDelta Seal that can significantly enhance the corrosion protection offered by zinc Plating. Zinc is an efficient, economical coating, with a minimal environmental impact. Plated zinc is *not* recommended for equipment that is continually immersed in solutions, petroleum applications, pharmaceutical applications, or food handling applications. Zinc should not be used in vacuum (spaceflight) applications (see NASA prohibition). It is also not recommended for aerospace applications.

The fundamental aim of zinc electroplating is to protect metals from rust or corrosion. Zinc plated coatings are also known as sacrificial coatings because the zinc coating sacrifices itself to protect the underlying metal from corrosion. In order to protect metals such as iron and steel from rusting, a process known as zinc electroplating is used. Zinc electroplating has to do with the electro-deposition of a thin layer of zinc metal on the surface of another metal which is known as substrate. The zinc coating serves as physical

protection which prevents rust from affecting the underlying metal surface. The reason why zinc is chosen is that of its ability to fight corrosion.

1.2 SELECTION OF ZINC COATINGS

Once the decision is made to use a zinc coating for corrosion protection, a few additional factors must be considered to ensure the proper coating is selected for the application and service environment. Each zinc coating covered in this section provides varying degrees of corrosion protection and it is important to identify the corrosiveness of the exposure environment to determine if the coating selected will provide adequate service life. Some zinc coatings will be eliminated by the nature alone, (zinc coating processes limited to small parts or sheet steels cannot be considered for the protective coating of structural steel members); others may be ruled out based on cost, appearance, availability, etc

1.3 THE BENEFITS OF ZINC ELECTROPLATING

Protection: Zinc plating is corrosion-resistant that slows rusting up to 30 years by keeping out the moisture lingering in air molecules. It also has a high-temperature tolerance up to 120°F while increasing the metal's life expectancy.

Ductility and Durability: Zinc is highly malleable, allowing it to stretch great lengths and mould into any shape. Its lightweight does not compromise the metal's functionality. Zinc is also a perfect option for undercoats.

Cost-Effective: Zinc is very affordable due to its abundance in nature. It is also recyclable and reusable.

Easy Process: Zinc plating is an easy application that is compatible with different plating procedures, such as rack and barrel plating. It can also handle high volume applications, which makes this specific plating very desirable.

Table 1.1 The coating densities, in terms of thickness required to equal 1 oz. of zinc per square foot of surface,

Method	Batch Hot-Dip Galvanizing	Continuous Sheet Galvanizing	Zinc Rich Painting	Metallizing	Mechanical Plating	Electro-galvanizing	Zinc Plating
Application/Venue Conditions	In shop factory-controlled; no special requirement	In shop factory-controlled; no special requirement	In shop or field; conditions are subjective and prone to human error	In shop or field	In shop factory-controlled; no special requirement	In shop factory-controlled; no special requirement	In shop factory-controlled; no special requirement
Specification	ASTM A123, A153, A767, CSA G164, ISO 1461	ASTM A653	SSPC-PS Guide 12.00, 22.00; SSPC-PS Paint 20; SSPC-PS 12.01	AWS C2.2	ASTM B695	ASTM A879	ASTM B633
Coating Thickness minimum/typical	1.4 to 3.9 mils ^a / 2 to 8 mils	0 to 3.2 mils ^b / 0 to 3.2 mils	0.6 to 5.0/ mils/coat/ 4.0 to 6.0 mils	3.3 mils/ 4.0 to 6.0 mils	0.2 to 4.2 mils ^c / 0.2 to 4.2 mils	0.28 mils ^b / 0 to 0.28 mils	0.2 to 1.0 mils ^c / 0.2 to 1.0 mils
Size	Fasteners to 90' beams	Sheet steel 0.010"-1.7" thick, 72" wide	Unlimited	Unlimited	Small parts 8"-9" and under 1 lb	Sheet steel	Small parts
Cure Time	<1 hour	<1 hour	24-72 hours	<24 hours ^d	<1 hour	<1 hour	<1 hour
Coverage Consistency	100% edges, corners, and interior > flat surfaces	Uniform thickness, controlled by air knife	Inconsistent, based on operator skill, tends to thin at edges and corners, interior surfaces are uncoated	Inconsistent based on operator skill	Inconsistent, thinner at edges, corners, and recesses	100% coverage	100% coverage
Bond to Substrate Steel	Metallurgical ~3,600psi	Metallurgical ~3,600psi	Mechanical 400-600 psi	Mechanical ~1,500 psi	Mechanical 400-600 psi	Mechanical 300-500 psi	Mechanical 300-500 psi
Abrasion Resistance/Hardness	Intermetallic layers 179-250 DPN	~70 DPN	Soft and not abrasion resistant	~70 DPN	75 DPN	~70 DPN	75 DPN
Finish/Appearance	Varies; matte gray, shiny, spangle, or combination	Controlled; minimum to highly spangled	Smooth finish; color to suit specifier	Matte gray, rough	Matte gray, rough compared to electro-plated	Smooth finish; shiny, unless passivated	Smooth finish; dull gray to shiny; controlled by additives
Exposure Conditions	Interior/exterior	Interior or mildly corrosive conditions	Interior/exterior	Interior/exterior	Interior/exterior	Interior	Interior
^a Range based on ASTM, ISO, and CSA minimum thicknesses for all grades, classes, etc., encompassed by the specifications. ^b Total for both sides of the sheet. ^c Range based on ASTM minimum thicknesses for all grades, classes, etc., encompassed by the specifications. ^d Dependent on sealer top coat.							

1.4 COATING THICKNESS VS. COATING WEIGHT

The service life of zinc coatings is a linear function of the zinc coating thickness. However, zinc coating thickness alone can be deceiving when evaluating zinc applied by different processes. In addition to thickness, the amount of available zinc per unit volume, or density, is also important. Various ASTM and/or other specifications require different weights or thicknesses, so it is imperative to convert all coatings to a common denominator for comparison. While coating densities for some types of zinc coatings are nearly identical, others differ considerably. The coating densities, in terms of thickness required to equal 1 oz of zinc per square foot of surface, are:

Table 1.2 The coating densities, in terms of thickness required to equal 1 oz of zinc per square foot of surface

Coating	Thickness to reach 1 oz/ft ²
Hot-dip galvanizing (batch or continuous), electroplating, zinc plating	1.7 mils (43 μm)
Metallizing (zinc spraying)	1.9 mils (48 μm)
Mechanical plating	2.2 mils (55 μm)
Zinc-rich paint	3-6 mils (75-100 μm)

Each of these thicknesses, representing the same weight per unit area of zinc, would be expected to provide equivalent service life; i.e. 1.7 mils of hot-dip galvanized would give about the same service life as 2.2 miles of mechanical plating or 3-6 mils (depending on the paint formulation) of zinc-rich paint, assuming bond strength and edge protection are not factors. It is also important to remember for all continuous galvanized sheet materials, including electrogalvanized, the coating weight is given for the total for both sides of the sheet. To obtain the amount of zinc per unit area of surface, the weight given must be divided in two, assuming equal distribution on both sides.

1.5 PROBLEM STATEMENT

Sacrificial Zinc electroplating coatings on high -strength steels is presented. These steels are used for heavy structural applications such as brakes assemble, that are subjected to high stresses and corrosive environment in service. The electroplating process involving aqueous electrolytes invariably produces hydrogen. The emitted hydrogen can diffuse into substrate steel, contributing to the delayed failures by hydrogen embrittlement. Baking after plating helps to eliminate hydrogen to some extent, though it may introduce some thermo mechanical stresses.

At present the zinc plating being carried out by 2 step sequences in Indian industries, hence the metal for which plating to be done will expose 2 times to the electrolytes. This increases the hydrogen production and in turn increases the hydrogen diffusion into substrate metal. To decrease the hydrogen embrittlement failures, a single step process is proposed for zinc plating.

CHAPTER – 2

2 LITERATURE SURVEY

2.1 LITERATURE 1

RuanWenbiao;Chen Lan; Li Zhigang; Ye Tianchun; Ma Tianyu; Wang QiangEffects of pattern characteristics on the copper electroplating process. International Nuclear Information System (INIS). 2011-01-01: The non-planarity of a surface post electroplating process is usually dependent on variations of key layout characteristics including line width, line spacing and metal density. A test chip is designed and manufactured in a semiconductor foundry to test the layout dependency of the electroplating process. By checking test data such as field height, array height, step height and SEM photos, some conclusions are made. Line width is a critical factor of topographical shapes such as the step height and height difference. After the electroplating process, the fine line has a thicker copper thickness, while the wide line has the greatest step height. Three typical topographies, conformal-fill, supper-fill and over-fill, are observed. Moreover, quantified effects are found using the test data and explained by theory, which can be used to develop electroplating process modelling and design for manufacturability (DFM) research. (Semiconductor integrated circuits)

2.2 LITERATURE 2

Islam, Aminul; Hansen, Hans NÃ,rgaard; Tang, Peter Torben; Direct electroplating of plastic for advanced electrical applications. DEFF Research Database (Denmark). 2017-01-01 Electrodeposition or electroplating is predominantly applied to metallic components. Electroplating of plastics is possible in some cases where an initial electroless plating layer of nickel or copper is made to provide a conductive surface on the plastic part. This paper proposes a method for direct electroplating of plastic eliminating the need for slow and expensive processes like electroless metal deposition, PVD coating, painting with conductive inks etc. The results obtained from the test demonstrate the potential of direct electroplating of plastic to enhance the electrical conductivity and the use of electroplated plastics for advanced applications like Moulded Interconnect Devices (MIDs).

2.3 LITERATURE 3

Li Zongwei; Yang Weifan; Fang Keming; Yuan Shuanggui; Guo Junsheng; Pan Qiangyan; Preparation of protactinium measurement source by electroplating method. International Nuclear Information System (INIS). 1998-01-01 An electroplating method for the preparation of Pa sources is described, and the main factors (such as pH value of solution, electroplating time and current density) influencing the electroplating of Pa are tested and discussed with ^{233}Pa as a tracer. A thin and uniform electroplating Pa-Layer of 1 mg/cm² thick on thin stainless-steel disk was obtained. The Pa source was measured by a HPGe detector to determine the chemical efficiency.

2.4 LITERATURE 4

Leigh, J. D. Electroplating eliminates gas leakage in brazed areas. Science.gov (United States). 1966-01-01 Electroplating method seals brazed or welded joints against gas leakage under high pressure. Any conventional electroplating process with many different metal anodes can be used, as well as the build-up of layers of different metals to any required thickness.

2.5 LITERATURE 5

Lowery, J. R. Electroplating on titanium alloy. Science.gov (United States) 1971-01-01 Activation process forms adherent electrodeposits of copper, nickel, and chromium on titanium alloy. Good adhesion of electroplated deposits is obtained by using acetic-hydrofluoric acid anodic activation process.

CHAPTER – 3

3. AIM & SCOPE OF ACID ZINC ELECTROPLATING

OBJECTIVE

- Automatic acid zinc plating process sequence reduction
- Automatic acid zinc plating cycle time reduction
- Increasing of automatic acid zinc plating production
- Automatic acid zinc plating operating cost reduction
- Automatic acid zinc plating manpower cost reduction

CHAPTER – 4

4. MATERIALS AND METHODOLOGY

4.1 DESIGN OF COMPONENT FOR ELECTROPLATING PLANT;

4.1.1 *Electroplating bath tank*

Electroplating bath box is made from acrylic sheet. The size of this plant length is 457mm, 304mm width 304mm, 5mm thickness. Acrylic is a plastic manufactured using one or more derivatives of acrylic acid. Polymethyl Methacrylate acrylic, or PMMA, is one of the more widely used forms of acrylic due to its exceptional weather ability, strength, clarity and versatility. There are a variety of acrylic polymer grades available for extrusion and injection molding manufacturing processes. Transparent, translucent opaque and colored polymers are available with varying levels of heat resistance, light transmissions, impact strength, flow rates and release capabilities. PMMA acrylic sheet exhibits glass-like qualities – clarity, brilliance, transparency, translucence – at half the weight with up to 10 times the impact resistance. It can be tinted or colored, mirrored or made opaque. A number of coatings can be applied to a sheet or finished part for performance enhancing characteristics such as scratch resistance, anti-fogging, glare reduction and solar reflectivity.

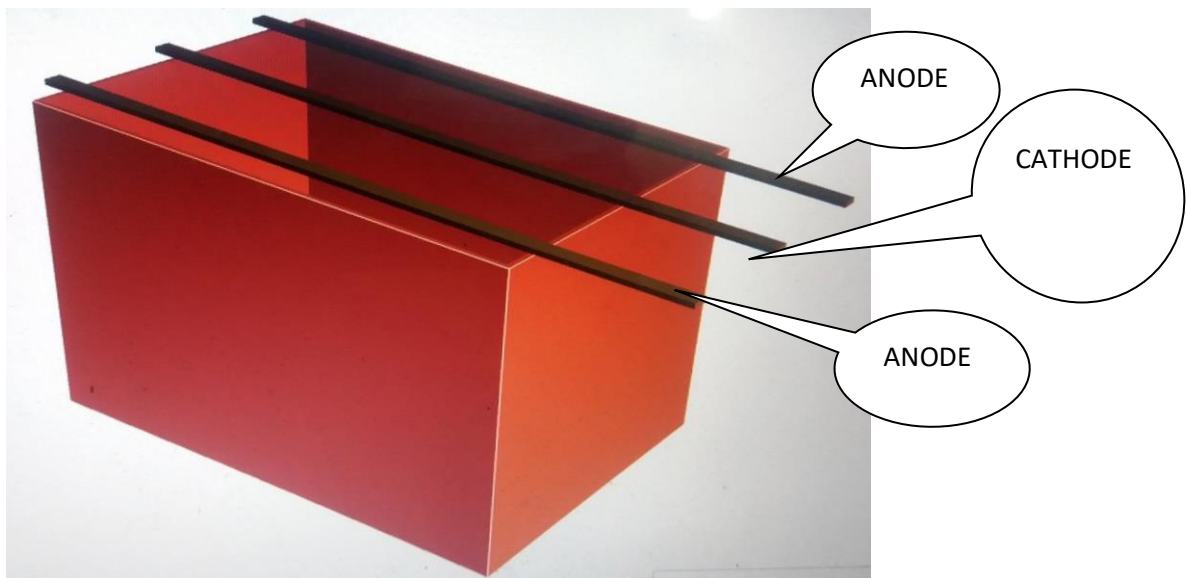


Fig: 4.1 Electroplating Bath Box

4.1.2 Electrode

The two types of electrodes which can be used in electroplating plant.

➤ **Anode**

The positively charged electrode by which the electrons leave an electrical device.

The negatively charged electrode of an electrical device, such as a primary cell, those supplies current.

➤ **Cathode**

The negatively charged electrode by which electrons enter an electrical device.

The positively charged electrode of an electrical device, such as a primary cell, that supplies current.

4.1.3 Power supply

A power supply is an electronic device that supplies electric energy to an electrical load. The primary function of a power supply is to convert one form of electrical energy to another and, as a result, power supplies are sometimes referred to as electric power converters. This is a transformer less power supply for low current applications. C1 is the X rated AC capacitor that reduces high volt AC. D1-D4 rectifies AC to DC and C2 removes ripples. R1 is the bleeder to remove stored current in AC when power is off. R2 limits inrush current. A Zener can be used in the output to get regulated DC. We use this power supply for convert 220 v AC to 12 V DC for ionization

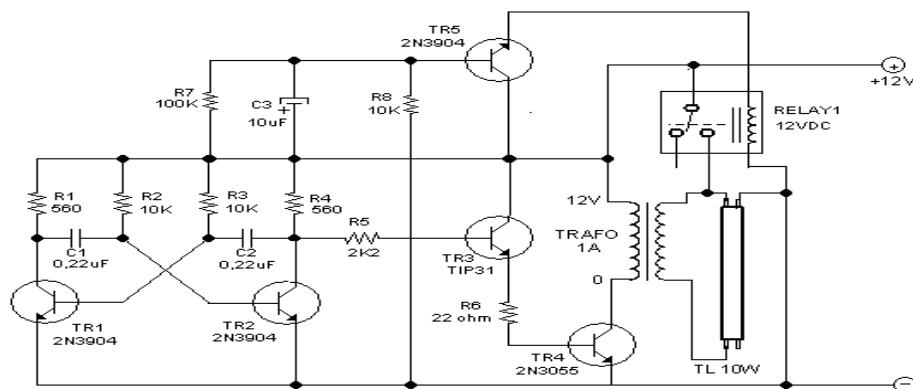


Fig: 4.2 220v primary 12v secondary step-down transformers

4.2 PROCESS SEQUENCE FOR ELECTRO PLATING

4.2.1 *Degreasing*

Solvent degreasing is a process used to prepare a part for further operations such as electroplating or painting. Typically, it uses petroleum, chlorine, or alcohol-based solvents to dissolve the machining fluids and other contaminants that might be on the part. We use clean agent AM104 with water. After making solution heat the solution 50~70 c and dipping the part for 5 minute. The ph. of solution 10~14.

4.2.2 *Rinsing water*

Rinse Water Options It may not be typical for all metal finishing operations but it is fairly common to have water costs at or near the top of the cost of operations. Rinsing is critical in the metal finishing process but more water use does not necessarily mean better rinsing.

- Best practices for producing effective rinsing are:
- Double counter flow immersion rinse tanks between process tanks.
- Reactive rinsing for the appropriate process chemistry combinations.
- Spray rinsing.
- Rinse controls such as automatic valves controlled by timers or water conductivity limits.
- We use the 10-liter water at normal temperature for rinsing.

4.2.3 *Acid pickling*

Pickling is a metal surface treatment used to remove impurities, such as stains, inorganic contaminants, and rust or scale from ferrous metals, copper, precious metals and aluminium alloys. A solution called pickle liquor, which usually contains acid, is used to remove the surface impurities. It is commonly used to de scale or clean steel in various steelmaking processes

4.2.4 *Passivation*

Using passivation is chromium (III) containing that produces a thick film passivation for zinc, which is completely free of chromium (VI), cobalt and fluoride. Passivation layers less sensitive to colour change after hydrogen de-embrittlement baking at 210° C for 6– 8

hours. Increases the corrosion protection and the colour stability after heat treatment due to nano particles inside.

4.2.5 Top coat

Topcoat is water dilutable, inorganic sealing system based on silicon. Topcoat is an inorganic sealing system which reacts with all passivates and chromates on top of zinc or zinc alloys. Topcoat achieves optimal results at a coating thickness between 0.5 to 2 microns.

4.3 EXPERIMENTAL STUDY OF ACID ZINC ELECTROPLATING

4.3.1 Previous Automatic Acid Zinc Plating Process Sequence 1

Indian automotive industry automatic acid zinc plating process with dual process sequence doing for hydrogen de embrittlement purpose of fastener parts, brakes assemble parts, harden screws. Dual process sequence it will be affect production yield, energy loss, cycle time increase due to the plating process cycle time for 15 minutes per load come. We have doing acid zinc plating with hydrogen de embrittlement step 1 and step 2 process sequence for following process flow diagram. Step 1 process details pre-treatment + acid zinc plating + activation + hydrogen de embrittlement then going to step 2 process. Purpose of pre-treatment basis material free from oils, grease, rust, organic oils. Acid zinc plating 8 to 12 micron coating thickness to help prevent corrosion of basis material like plating parts (mild steel). After plating doing activation, it helps to removed organic layer from plating parts and improve brightener in overall surface then moved to hydrogen de embrittlement process.

Hydrogen de embrittlement oven we have maintained temperature 180°C to 220°C it eliminated hydrogen molecular from plating parts. If hydrogen not removed from plating parts, the component will be broken for sudden period of time. Hydrogen molecular adsorption from acid pickling to plating object reason for most of hydrogen reaction with acid pickling bath solution because we have using hydrochloric acid 30 to 35 % of concentration. Step 2 process detail after hydrogen de embrittlement process plating parts move to acid zinc flash plating with 2 to 4 micron coating thickness. Then doing trivalent passivation 200 to 350 nano meter with sealer because of passivation layer it helps to increase corrosion life and sealer layer 1 to 2 micron it also helps to increase corrosion life.

reason for flash plating after hydrogen de embrittlement process plating part overall surface affect the brightener (visual appearance) so we have doing flash acid zinc with 2-to-4-micron coating thickness it helps to improved brightener of plating parts.

4.3.2 Current Automatic Acid Zinc Plating Process Sequence

We have single step acid zinc plating process sequence trial conducted at M/S bright electro process. About bright electro process he is doing acid zinc plating with hydrogen de embrittlement process past 42 years and bright electro process tier 1 and tier 2 supplier for all OEMs like Hyundai, Maruti, Ford. previously bright electro process using dual process acid zinc plating it also high economy, difficult process step. We have trial doing single step process sequence for following process flow diagram. single step process sequence details pre-treatment + acid zinc plating + trivalent passivation + sealer + hydrogen de embrittlement process. single step process sequence eliminated flash acid zinc plating process because of not required because we have using passivation solution with silica liquid nano particle it helps to improve plating part corrosion life and after hydrogen de embrittlement surface of part improved brightener, colour stability. topcoat/sealer chemical also including silica particle it penetrates with chrome layer and zinc layer because of using sealer is reactive sealer. Sealer information is a water dilutable, inorganic sealing system based on silicon and contains no chromates in the dry film and does not produce hydrogen embrittlement into the coated material. The dry film is transparent. Sealer is an inorganic sealing system which reacts with all our passivates and chromates on top of zinc or zinc alloys. achieves optimal results at a coating thickness between 0.5 and 2 microns and is used on fasteners like bolts, screws, nuts, springs, clamps, stampings etc. passivation produces iridescent passivate layers on zinc surfaces.

Passivation is a completely fluoride free passivate. Passivation layers are less sensitive to colour change after hydrogen de-embrittlement heat treatment of the respective Zn layer. Passivation has excellent corrosion protection. Single step process sequence advantage increase production yield, easy maintenance, energy save, process cost saves, manpower save. We have mentioned advantage details in performance analysis and trial results.

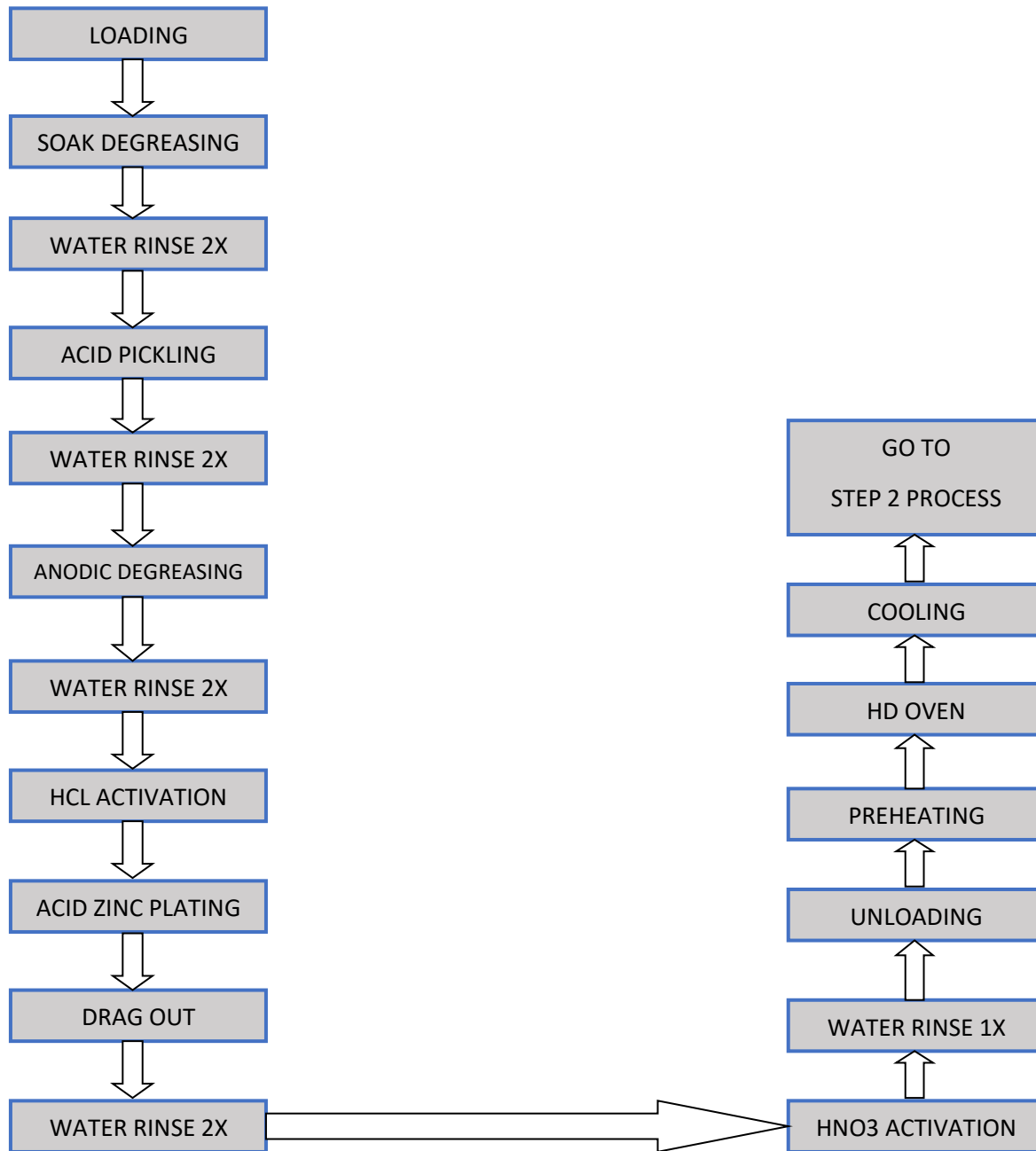


Fig: 4.3 Step 1 Of Previous Acid Zinc Plating Process Sequence

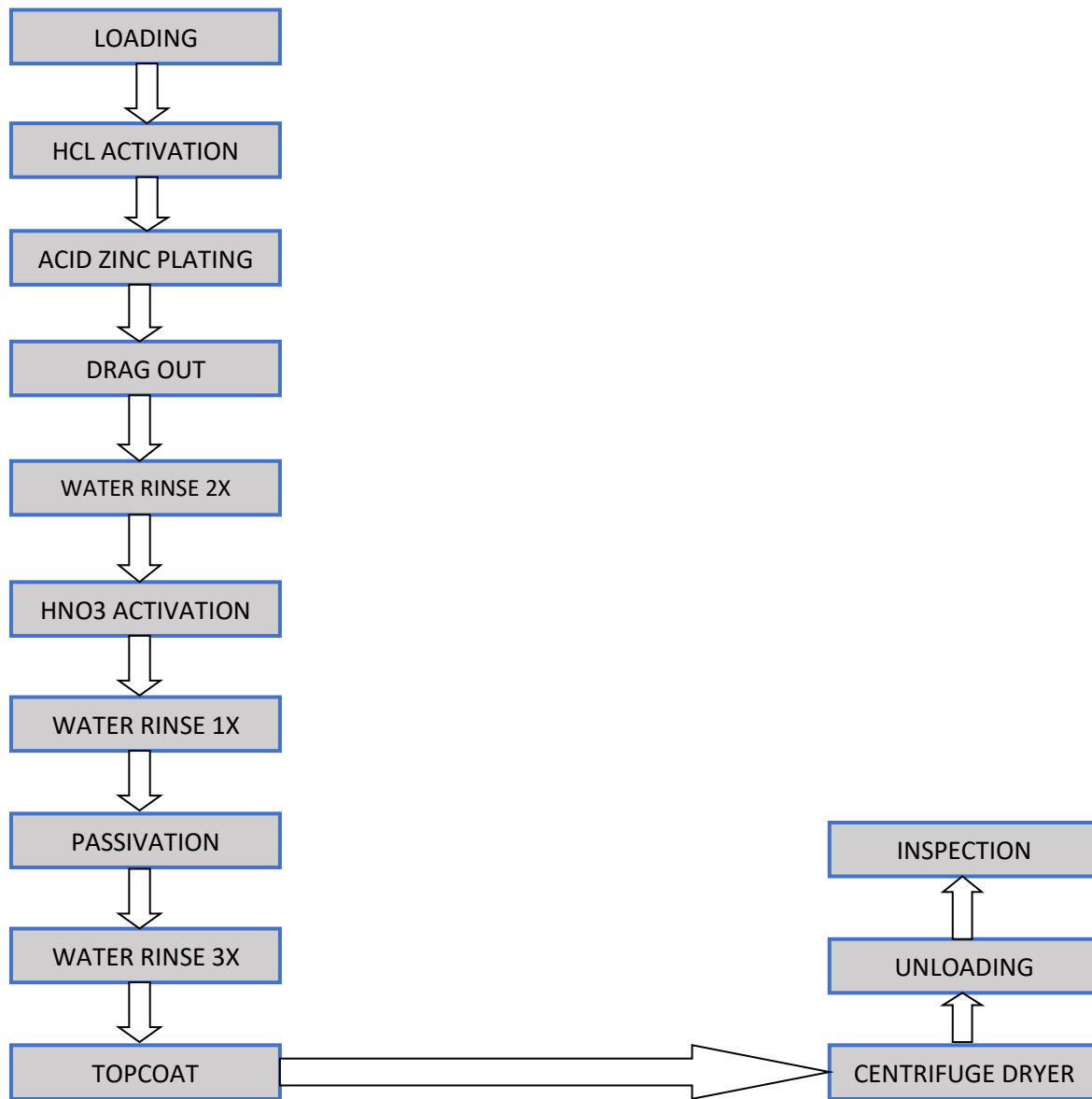


Fig: 4.4 Step 2 Previous Acid Zinc Plating Process Sequence

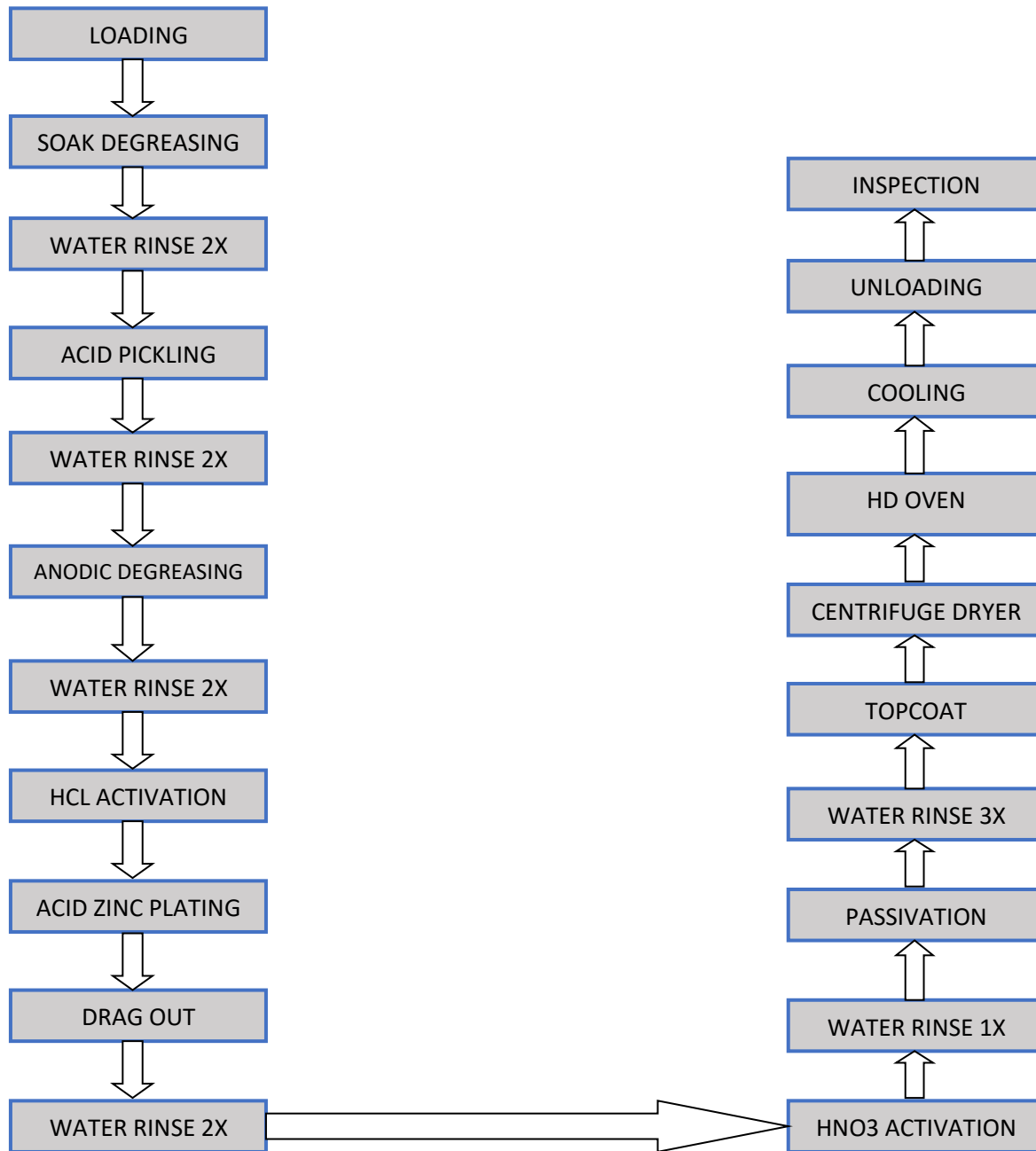


Figure: 4.5 Single Step Acid Zinc Plating Process Sequence

4.3.3 Hydrogen Embrittlement and Electroplating

The electroplating process involves the use of an aqueous electrolyte solution (known as the plating “bath”) that consists of dissolved metal salts, ions and various chemicals. However, the primary bath component is something we all use every day: water. As most of us learned in elementary school, every water molecule is comprised of two hydrogen atoms and one oxygen atom, resulting in the familiar formula of H₂O.

As the electroplating process typically involves the immersion of the substrate into the plating bath, hydrogen from the water may be co-deposited onto the surface of the substrate along with the metal ions. This can result in a potentially harmful condition known as hydrogen embrittlement.

4.3.4 What Is Hydrogen Embrittlement

Hydrogen embrittlement is a loss of ductility due to excess hydrogen absorption, which makes the material brittle. It occurs because hydrogen atoms are much smaller than those that comprise the deposited metal. This causes the hydrogen atoms to migrate into the crystal lattice of the base metal and become lodged between the individual metal atoms. This can substantially increase the stress of applied forces within the base metal and result in fracturing. Hydrogen embrittlement can also occur during pre-plating processes such as cleaning and pickling, as well as during electroless plating procedures.

4.3.5 How To Prevent Hydrogen Embrittlement

While hydrogen embrittlement can cause significant damage to a part, there are a number of techniques that can prevent it from occurring.

4.3.6 Post Plating Baking

Baking the part immediately after plating can reverse the effects of hydrogen embrittlement in most cases. General guidelines call for baking the part for four hours at a temperature of 375° F within one hour of plating. Most steels typically require a lower temperature in the range of 200-300° F.

4.3.7 Adding Inhibitors during Pickling

Corrosion of the base metal may occur during pickling, leading to vigorous hydrogen evolution that in turn may cause embrittlement. The use of inhibitors during the pickling step can reduce or eliminate this corrosion, resulting in a decrease in hydrogen pick-up.

4.3.8 Substituting Metal Alloys

Certain metals, particularly extremely high-strength steels, are more susceptible to hydrogen embrittlement than others. Alloying these high-risk metals with ones exhibiting lower hydrogen diffusion rates such as nickel, zinc or molybdenum can be extremely effective in preventing hydrogen embrittlement.

CHAPTER 5

5. PERFORMANCE ANALYSIS

5.1 PROCESS SPECIFICATION

Table 5.1 Passivation and Sealer Parameter Details

PROCESS DESCRIPTION	PARAMETERS	SPECIFICATION RANGE	ACTUAL
PASSIVATION	concentration in ml/lit	100 - 120 ml/lit	120 ml/lit
	pH	1.6 - 2.0	2
	time	30 - 90 sec	60 sec
	temp °c	room temperature	room temperature
	nano particles	10 - 20 ml/lit	15 ml/lit
TOPCOAT	concentration in ml/lit	100 - 200 ml/lit	150 ml/lit
	pH	9.5 - 10.5	10
	time	10 - 20 sec	20 sec

Table 5.2 Process Cycle Time Comparison of Previous V/S Current

PREVIOUS	CURRENT
step 1 process cycle time per load 60 minutes	single step process cycle time per load 90 minutes
step 2 process cycle time per load 90 minutes	step 2 process eliminated in current acid zinc plating line
total cycle time 150 minutes	total cycle time 90 minutes

Table 5.3 Production Yield Comparison of Previous vs Current

PREVIOUS	CURRENT
As per cycle time per load 150 minutes	As per cycle time per load 90 minutes
per load quantity 50 kgs	per load quantity 50 kgs
one hour production yield 200 kgs	one hour production yield 300 kgs
per day production yield 4800 kgs	per day production yield 7200 kgs

5.2 PROCESS COST COMPARISON OF PREVIOUS V/S CURRENT

Table 5.4 Previous Process Cost Details

S.No.	Process	RUNNING COST		
		Consumption/sq. ft in gm/ml	Costing Paisa /sq. inch	Costing Rs /sq.ft
1	Soak Cleaning 1	2.32	0.2	0.29
2	Anodic Cleaning	1.39	0.12	0.18
			0.33	0.47
3	Acid Zinc Plating	0.19	0.03	0.04
		0.46	0.07	0.1
		0.93	0.07	0.09
		5.58	0.43	0.61
		0.46	0.08	0.11
4	Acid Zinc flash plating	0	0	0
		0	0	0
		0.93	0.07	0.09
		5.58	0.43	0.61
		0.46	0.08	0.11
			1.24	1.78
5	Passivation Cr3	1.86	0.4	0.58
			0.4	0.58
6	Sealer	1.86	0.56	0.81
			0.56	0.81
		Overall cost	2.53	3.64

Table 5.5 Current Process Cost Details

S.No.	Process	RUNNING COST		
		Consumption/Sq. ft in gm/ml	Costing Paise / Sq. inch	Costing Rs /Sq.ft
1	Soak Cleaning	2.32	0.2	0.29
2	Anodic Cleaning	1.39	0.12	0.18
			0.33	0.47
3	Acid Zinc Plating	0.19	0.03	0.04
		0.46	0.07	0.1
		0.93	0.07	0.09
		5.58	0.43	0.61
		0.46	0.08	0.11
			0.67	0.96
4	Passivation Cr3	0.93	0.2	0.29
			0.2	0.29
5	Sealer	0.93	0.28	0.4
			0.28	0.4
	Overall cost		1.47	2.12

Table 5.6 Manpower Cost Comparison of Previous vs Current

DESCRIPTION	MANPOWER QUANTITY	
	PREVIOUS	CURRENT
loading	2	1
unloading	2	1
line incharge	1	1
dryer operator	2	1
visual inspection	2	2
one manpower cost Rs	1000	1000
total manpower quantity	9	6
total manpower cost	9000	6000

6. RESULTS AND DISCUSSION

6.1 ELECTROPLATING FINAL PRODUCT FINISH



Fig 6.1 Before Oven Finish for Strut



Fig 6.2 After Oven Finish for Strut



Fig 6.3 Final Finish for Strut



Fig 6.4 Before Oven Finish for Screw



Fig 6.5 After Oven Finish for Screw



Fig 6.6 Final Finish for Screw

6.2 COATING THICKNESS REPORT STRUT



ISO 9001:2015 CERTIFIED

CONSOLIDATED METAL FINISHING (P) LTD

NO: 104, (N.P) INDUSTRIAL ESTATE, AMBATTUR, CHENNAI-600098.

TEL: 044 - 26253976; FAX: 91-44-26241088. E-mail: lab@cmf-india.com

COATING THICKNESS TEST REPORT (Tested in XRF)

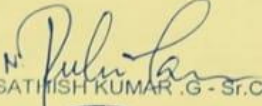
Customer Name : Bright Electro Process
Plating Details : Zinc plating with Trivalent yellow passivation
Part Name & No : Strut

Date : 01.08.2022



n=	1	Cr 1 =	0.186 μm	Zn 2 =	9.092 μm
n=	2	Cr 1 =	0.174 μm	Zn 2 =	9.417 μm
n=	3	Cr 1 =	0.175 μm	Zn 2 =	7.235 μm
n=	4	Cr 1 =	0.228 μm	Zn 2 =	8.655 μm
n=	5	Cr 1 =	0.205 μm	Zn 2 =	10.52 μm
n=	6	Cr 1 =	0.131 μm	Zn 2 =	10.60 μm

Mean	0.183 μm	9.253 μm
Number of readings	6	6
Min. reading	0.131 μm	7.235 μm
Max. reading	0.228 μm	10.60 μm
Measuring time	20 sec	

Tested By :  SATISH KUMAR .G - Sr.Chemist.



6.3 COATING THICKNESS REPORT SCREW



ISO 9001:2015 CERTIFIED

CONSOLIDATED METAL FINISHING (P) LTD

NO: 104, (N.P) INDUSTRIAL ESTATE, AMBATTUR, CHENNAI-600098.

TEL: 044 - 26253976; FAX: 91-44-26241088. E-mail: lab@cmf-india.com

COATING THICKNESS TEST REPORT (Tested in XRF)

Customer Name : Bright Electro Process
Plating Details : Zinc plating with Trivalent yellow passivation
Part Name & No : Screw

Date : 01.08.2022



n=	1	Cr 1 =	0.158 μm	Zn 2 =	11.34 μm
n=	2	Cr 1 =	0.173 μm	Zn 2 =	10.43 μm
n=	3	Cr 1 =	0.166 μm	Zn 2 =	8.111 μm
n=	4	Cr 1 =	0.183 μm	Zn 2 =	9.125 μm
n=	5	Cr 1 =	0.161 μm	Zn 2 =	9.173 μm
n=	6	Cr 1 =	0.145 μm	Zn 2 =	10.69 μm

Mean	0.164 μm	9.811 μm
Number of readings	6	6
Min. reading	0.145 μm	8.111 μm
Max. reading	0.183 μm	11.34 μm
Measuring time	20 sec	

Tested By : SATHISH KUMAR .G - Sr.Chemist.



6.4 PLATING ADHESION TEST REPORT STRUT

ElectroChem Technologies India Pvt. Ltd.,

No. 4D/ 1-A, 8th Street, 3rd Main Road,
Ambattur Industrial Estate,
Chennai 600 058, TamilNadu, India
Phone # + 91 44 26520024/ + 91 44 26520064
Fax # + 91 44 26520064
E Mail: lab@electrochemtechnologies.com



TEST REPORT

Customer: M/s BRIGHT ELECTRO PROCESS	Report No/ Date	7.2.2_3/LAB_354 Dt: 02.08.2022
	Date of Testing	02.08.2022
	Samples Received on	02.08.2022
	Sample Drawn by	Customer
	Part No :	STRUT
	Qty :	1 No

THERMAL TEST :

PARAMETERS :

TEMPERATURE : 150⁰C

TIME : 1 HOUR

STARTING TIME : 11.50 AM

ENDING TIME : 12.50 PM

IMMEDIATELY DIPPED IN WATER AT ROOM TEMPERATURE FOR 10 seconds.

RESULT :

After dipping in water,

1. No Blisters were present.
2. No Peel Off.

ElectroChem Technologies India Pvt. Ltd.,

No. 4D/ 1-A, 8th Street, 3rd Main Road,
Ambattur Industrial Estate,
Chennai 600 058, TamilNadu, India
Phone # + 91 44 26520024/ + 91 44 26520064
Fax # + 91 44 26520064
E Mail: lab@electrochemtechnologies.com



PICTURE OF THE COMPONENT:

BEFORE QUENCHING :



AFTER QUENCHING:



Verified By : SURESH KUMAR R

.....Concluded.....

For ElectroChem Technologies India Pvt.Ltd.

Authorised Signatory.

6.5 PLATING ADHESION TEST REPORT SCREW

ElectroChem Technologies India Pvt. Ltd.,

No. 4D/ 1-A, 8th Street, 3rd Main Road,
Ambattur Industrial Estate,
Chennai 600 058, TamilNadu, India
Phone # + 91 44 26520024/ + 91 44 26520064
Fax # + 91 44 26520064
E Mail: lab@electrochemtechnologies.com



TEST REPORT

Customer: M/s BRIGHT ELECTRO PROCESS	Report No/ Date	7.2.2_3/LAB_355	Dt: 02.08.2022
	Date of Testing	02.08.2022	
	Samples Received on	02.08.2022	
	Sample Drawn by	Customer	
	Part No :	SCREW	
	Qty :	1 No	

THERMAL TEST :

PARAMETERS :

TEMPERATURE : 150⁰C

TIME : 1 HOUR

STARTING TIME : 11.50 AM

ENDING TIME : 12.50 PM

IMMEDIATELY DIPPED IN WATER AT ROOM TEMPERATURE FOR 10 seconds.

RESULT :

After dipping in water,

1. No Blisters were present.
2. No Peel Off.

ElectroChem Technologies India Pvt. Ltd.,

No. 4D/ 1-A, 8th Street, 3rd Main Road,
Ambattur Industrial Estate,
Chennai 600 058, TamilNadu, India
Phone # + 91 44 26520024/ + 91 44 26520064
Fax # + 91 44 26520064
E Mail: lab@electrochemtechnologies.com



PICTURE OF THE COMPONENT:

BEFORE QUENCHING :



AFTER QUENCHING:



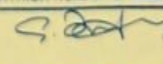
Verified By : SURESH KUMAR R

.....Concluded.....

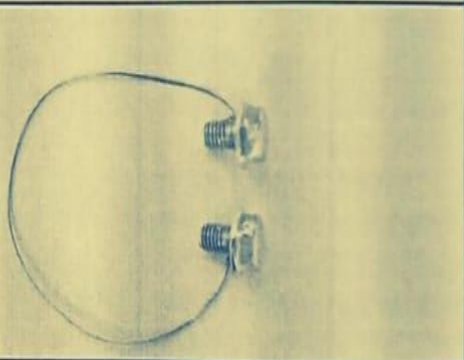
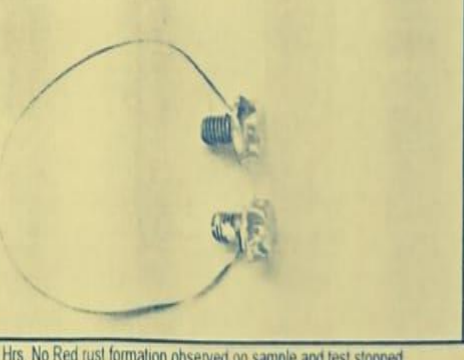
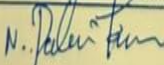
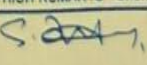
For ElectroChem Technologies India Pvt.Ltd.

Authorised Signatory.

6.6 SALT SPRAY TEST REPORT STRUT

 Consolidated Metal Finishing Pvt Ltd., Chennai - 600 098.		SALT SPRAY TEST REPORT		
COMPANY NAME : M/S BRIGHT ELECTRO PROCESS PART NAME & NO : STRUT & 4801 DESCRIPTION : Alkaline Zinc Plating with Trivalent yellow passivation & Sealer THICKNESS DETAILS : Chromate - 183 Nanometer & Thickness - 9.253 Microns. CUSTOMER SPECIFICATION : 96 Hrs to 5% W.R and 240 Hrs to R.R formation		TEST METHOD :- ASTM B117 / ISO 9227 NaCl CONCENTRATION : 5% $\pm$ 0.5% (BY WEIGHT) AIR PRESSURE : 10 - 20 Psi AIR SATURATOR TEMP : 47 °C $\pm$ 1 °C CHAMBER TEMP : 35 °C $\pm$ 2 °C Starting Date of Test : 02.08.2022 Closing Date of Test : 17.08.2022		
TEST DURATION	OBSERVATION	SAMPLE PHOTO'S		REMARKS
24 Hrs	No changes observed.	SAMPLE PHOTO AT 168 HRS IN SST		
48 Hrs	-----			
72 Hrs	-----			
96 Hrs	-----			
120 Hrs	Mild Black dots observed.			
144 Hrs	1 - 2% W.R Observed			
168 Hrs	5% W.R Observed			
192 Hrs	> 5% W.R Observed			
216 Hrs	No Red rust formation observed			
240 Hrs	-----			
264 Hrs	No Red rust formation observed			
	(Test Stopped)			
TEST RESULT : At 168 Hrs, 5% White rust observed & Upto 264 Hrs, No Red rust formation observed on sample and test stopped.				
PREPARED BY : N.PALANI KUMAR - Chemist 		APPROVED BY : SATHISH KUMAR - Chemist. 		

6.7 SALT SPRAY TEST REPORT SCREW

 Consolidated Metal Finishing Pvt Ltd., Chennai - 600 098.		SALT SPRAY TEST REPORT		
		Date : 17.08.2022 Report No : 110 / 02		
COMPANY NAME : M/S BRIGHT ELECTRO PROCESS PART NAME & NO : SCREW DESCRIPTION : Alkaline Zinc Plating with Trivalent yellow passivation & Sealer THICKNESS DETAILS : Chromate - 164 Nanometer & Thickness - 9.811 Microns CUSTOMER SPECIFICATION : 96 Hrs to 5% W.R and 240 Hrs to R.R formation		TEST METHOD :- ASTM B117 / ISO 9227 NaCl CONCENTRATION : 5% $\pm$ 0.5% (BY WEIGHT) AIR PRESSURE : 10 - 20 Psi AIR SATURATOR TEMP : 47 °C $\pm$ 1 °C CHAMBER TEMP : 35 °C $\pm$ 2 °C Starting Date of Test : 02.08.2022 Closing Date of Test : 17.08.2022		
TEST DURATION	OBSERVATION	SAMPLE PHOTO'S	REMARKS	
24 Hrs	No changes observed.			
48 Hrs				
72 Hrs				
96 Hrs	Mild Black dots observed.			
120 Hrs	1 - 2% W.R Observed			
144 Hrs	5% W.R Observed			
168 Hrs	> 5% W.R Observed			
192 Hrs	No Red rust formation observed			
216 Hrs				
240 Hrs				
264 Hrs	No Red rust formation observed			
	(Test Stopped)			
TEST RESULT : At 144 Hrs, 5% White rust observed & Upto 264 Hrs, No Red rust formation observed on sample and test stopped.				
PREPARED BY : N.PALANI KUMAR - Chemist 		APPROVED BY : SATHISH KUMAR, G - Chemist 		

6.8 CONCLUSIONS

An extensive review of the Zn sacrificial electroplating of high strength steels and their stability under hydrogen embrittlement has been provided. Automatic acid zinc plating screw and strut parts trial conducted at bright electro process. The trial results were eliminated dual step electro plating process and introduced single step electro plating process. Automotive OEM's requirement meets out single step electro plating process for like natural salt spray test, coating thickness, Adhesion test and visual appearance. Automatic acid zinc plating single step process method reduce the cycle time, improved production yield, reduce process cost and manpower cost compared to dual step electro plating process.

REFERENCES

1. Alzahrany, R.A. (2017). Corrosion fatigue behavior of AISI 4340 steel coated with cadmium and zinc-nickel with and without scribed damage in saltwater environment, MS Thesis. Air Force Institute of Technology, Wright-Patterson Air Force Base, AFIT-ENY-MS 17-S-001, Ohio.
2. ASM Handbook (2016). Ni (Nickel) binary alloy phase diagrams, in alloy phase diagrams. In: Okamoto, H., Schlesinger, M.E., and Mueller, E.M. (Eds.), Alloy phase diagrams, Vol. 3. ASM International, OH, USA.
3. Badeshia, H.K.D.H. (2016). Prevention of hydrogen embrittlement in steels. *ISI J Int.* 56: 24–36.
4. Bandhopadhyay, N., Kamada, J., and McMahon, C.J., Jr. (1983). Hydrogen -induced cracking in 4340-type steel: effects of composition, yield strength, and H₂ pressure. *Metall. Trans. A* 14A: 881–888.
5. Beachem, C.D. (1972). A new model for hydrogen-assisted cracking (hydrogen embrittlement). *Metall. Trans.* 3: 437–451.
6. Brown (NAVAIR), S.A., Berman (Airforce), E. (2011). Cadmium alternatives for high-strength steel. SBIR Final Rep., Vol. 5, WP 200022.
7. Conde, A., Arenas, M.A., and de Damborenea, J.J. (2011). Electro deposition of Zn–Ni coatings as Cd replacement for corrosion protection of high strength steel. *Corrosion Sci.* 53:1489–1497.
8. Constantin, I. (2014). Microstructural characterization and corrosion behavior of electroless Ni-Zn-P thin films. *J. Metall.* 2014: 6, Article ID 827393.
9. Durairajan, A., Haran, B.S., White, R.E., and Popov, B.N. (2000). Development of a new electrodeposition process for plating of Zn-Ni-X (X5Cd, P) alloys I. Corrosion characteristics of Zn-Ni-Cd ternary alloys. *J. Electrochem. Soc.* 147: 1781–1786.
10. Eliaz, N., Venkatakrishna, K., and Hegde, A.C. (2010). Electroplating and characterization of Zn–Ni, Zn–Co and Zn–Ni–Co alloys. *Surf. Coating. Technol.* 205: 1969–1978.
11. Evans, A.G. and Hutchinson, J.W. (1995). The thermomechanical integrity of thin films and multilayers. *Acta Metall. Mater.* 43:2507–2530.

12. Evans, J.M. (1992). Effect of nickel plating on the hydrogen embrittlement of high strength steels, Ph.D. thesis. Cranfield Institute of Technology, School of Industrial Manufacturing Science, Cranfield.
13. Fashu, S. and Khan, R. (2019). Recent work on electrochemical deposition of Zn-Ni (-X) alloys for corrosion protection of steel. *Anti-corrosion Methods & Mater.* 66: 45–60.
14. García-Antón, J., Fernández-Domene, R.M., Sánchez-Tovar, R., Escrivà-Cerdán, C., Leiva-García, R., García, V., and Urtiaga, A. (2014). Improvement of the electrochemical behavior of Zn-electroplated steel using regenerated Cr (III) passivation baths. *Chem. Eng. Sci.* 111: 402–409.
15. Gordon, F. (2005). Hydrogen re-embrittlement susceptibility of ultrahigh strength steels, Cranfield University, School of Industrial and Manufacturing Science, Ph.D. Thesis. Cranfield University. Hall, D.E. (1983). Electrodeposited zinc-nickel alloy coating – a review. *Plat. Surf. Finish.* 70: 59–65.
16. Harvey, W.E. (1930). Zinc as a protective coating against corrosion. *Fatig. Steel, Metals, Alloys* 1: 458.
17. Hegde, A.C. and Thangaraj, V. (2009). Electro deposition and characterization Zn-Co alloy. *Russ. J. Electrochem.* 45: 756–761.
18. Johnson, H.H. (1969). Fundamental Aspects of stress corrosion cracking, NACE, 439.
19. McMahon, C.J., Jr., Takayama, S., Ogura, T., Fu, S.C., Murza, J.C., Graham, W.R., Yen, A.C., and DiDio, R. (1980). Elimination of impurity-induced embrittlement in steel Part 1: impurity segregation and temper embrittlement, N P-1501. Report for Electric Power Research Institute 3412 Hillview Avenue Palo Alto, California 94304.
20. Northrop Aircraft, Inc (1959). Methods of testing for hydrogen embrittlement', final report on ARTC project W-95, REPORT NO. NOR-59-4,72.
21. Oriani, R.A. and Josephic, P.H. (1974). Equilibrium aspects of hydrogen induced cracking of steels. *Acta Metall.* 22: 1065–1074.

