IC LEARNING SERIES

Surface Finishing
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CCN3125 Appreciation of Manufacturing Processes
ICU328 Practical Appreciation of Electro-Mechanical Automation System

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Surface Finishing

Objectives:

✓ To understand the basic knowledge of Surface Finishing
✓ To be capable of performing the essential manufacturing processes in Surface Finishing
✓ To recognize the importance of safety in Surface Finishing

1. Introduction

Surface finish may be defined as an operation applied to the surface of an article (metal/non-metal) in order to lend it properties/appearance not possessed by the article in its 'unfinished' form. It may simply imply polishing to make it smooth; a coating may be applied to the surface to change its appearance and properties.

The main functions of surface finishing are:

- To improve surface appearance
- To enhance corrosion resistance
- To impart the required surface properties

1.1 Decorative Finishing

In terms of commercial importance, decorative application represents the bulk quantity in surface finished products. Some finishes for outdoor uses require both corrosion resistance and good appearance. Some objects meant to be used indoors, in dry environments and where danger of corrosion is slight are finished with lacquers, paints, electroplated coatings etc. for purely aesthetic reasons. The very thin layer of gold or silver applied to some inexpensive jewelry has little or no protective value; it is there principally to attract potential buyers.

1.2 Corrosion Resistance

1.2.1 Protection of steel

Steel is the most widely used metallic materials; it comprises 80% plus by weight of all metals and alloys used. Its mechanical properties out performs most other materials and is the cheapest; but steel is not very resistant to corrosion, a surface coating must be applied to separate the steel from the atmosphere, or to protect it electrochemically from corrosion.
It may be electroplated, hot dip galvanized, painted, porcelain enamel coated, or finished in other ways. Many foods and beverages are not highly corrosive to steel, but even traces of iron would spoil their taste or acceptability; thus the steel cans are plated with tin.

### 1.2.2 Other metallic materials

Except aluminium alloys, chromium, stainless steel and noble metals of gold, platinum, palladium, rhodium etc. most metals will tarnish with time, they need to be protected from corrosion, as well as for decorative purposes.

In some cases base metals need to be protected from their environments even though they do not corrode very much. For example, many chemical and pharmaceutical plants are very sensitive to traces of contaminants, so they must be protected with suitable coatings.

### 1.3 Surface properties

Surface finishing is also applied to obtain some desirable surface properties not possessed by base metals. For example, electroless nickel alloy plating, hard chromium plating applied to moving parts/plastic moulds for wear resistance, Teflon coating on cooking pans for non-stick purpose, titanium nitride on drills to impart high hardness etc.

### 2. Pretreatment

Prior to electroplating or any surface coating process, pretreatment is the most important, since the quality of the deposition greatly depending upon the cleanliness and texture attained by pretreatment.

A clean surface for electroplating should be:
- Free from oil, grease, gross defect, rust or oxide film etc.
- Free from severe work hardening;
- Active and easy to deposit a metal coating.

#### 2.1 Mechanical Surface Preparation

##### 2.1.1 Grinding, Polishing and buffing

Grinding involves the use of sanding machine, hand file, grinding wheel or sandpaper. Where abrasive grits are bonded on the paper/cloth/abrasive disc. Grinding leaves a fairly rough surface. Polishing follows grinding and proceeds buffing. The purpose of polishing is to remove a significant amount of metal and to smooth the surface in a preliminary way, preparatory to the more refined smoothing offered by buffing. Buffing usually follows polishing and further smoothes the surface and improves its appearance, but removes little metal.
2.1.2 Abrasive blasting (Sand blasting)

Abrasive blasting is a process for cleaning and matt finishing the surface by forcefully directed spray of abrasive grains either dry or suspend in a liquid against the surface of the article.

Abrasive blasting is used for:

i. To remove scale, rust, paint and soil etc.;
ii. To roughen the surface for painting or other coating.
iii. To remove metal 'flash' or for deburring.
iv. Matt finishing not only for metals but also for glasses and plastics.

2.1.3 Polishing and Buffing

High-speed rotating mops are used in polishing and buffing to produce a smooth and reflective surface. The cloth mops are mounted on the polishing/buffing machine and coated or smeared with polishing or buffing compounds. The sizes and shapes of the mops are different, and must be chosen properly according to the configuration and sizes of the articles to be finished. The selection of the different kinds of abrasive or polishing compounds depends on the required surface texture to be obtained and the kind of metallic material to be treated.

The polishing/buffing operation:

i. Preliminary abrasive finishing: Using fast cutting abrasive coated mop and bob;
ii. Bright buffing: Using softer mop with the different sorts of the buffing compound.

Sometimes the articles which have been plated with copper, nickel, chromium, silver etc. might be buffed to provide more brightness.

2.2 Chemical Surface Preparation

2.2.1 Solvent Clean

It is the cleaning process by using the effective organic solvent to remove gross heavy soil, oil and grease prior to the other cleaning cycle. The parts being cleaned is immersed or suspended into a container in which the solvent has been vaporized. The most commonly used solvent is hydrocarbon cleaner. Adequate ventilation must be provided in using organic solvents.

2.2.2 Ultrasonic clean

Ultrasonic clean depends on the cavitations that producing rapid formation and rapid collapse of minute bubbles in the cleaning liquid. This agitation by countless small and intense implosion bubbles produce an effective scrabbling action on the exposed even the hidden or recessed parts of the article being cleaned.
The main component of the ultrasonic clean device is transducer. It can convert electrical energy to ultrasonic vibration (frequency is above 20,000 cycles per second).

The type of the transducer is piezoelectric or magnetostrictive made of nickel or its alloys or electrostrictive made of lead zirconate or barium titanate and other type such as polarised ceramic.

### 2.2.3 Electrolytic alkaline clean

It is more rapid and reliable way for cleaning the surface than soak alkaline clean. In the electrolytic alkaline clean the articles are made cathodic or anodic, the gases are liberated at the surface of the article and would cause mechanical agitation and scrubbing action to dislodge soil and contaminants on the surface.

Anodic reaction: \[ 4\text{(OH)} \rightarrow (-4e^-) 2\text{H}_2\text{O} + \text{O}_2 \uparrow \]

Cathodic reaction: \[ 4\text{H}^+ \rightarrow (+4e^-) 2\text{H}_2 \uparrow \]

Cathodic cleaning would evolve twice as much volume of hydrogen as the oxygen at the anode side at a given current density, so the cathodic cleaning is more effective degreasing process than the anodic cleaning.

Positive charged ions such as Cu$^{+2}$, Zn$^{+2}$, Fe$^{+2}$ could be deposited and formed a metallic smut at the cathode. So, different solution should be applied when the non-ferrous metals are to be cleaned.

Hydrogen gases evolved at the cathode may penetrate into the steel or other ferrous metals.

Certain ferrous metals may be susceptible to hydrogen embrittlement. For this reason, an anodic cleaning cycle is usually applied after cathodic cleaning or, uses anodic cleaning alone in order to avoid embrittlement of the ferrous metal.
Anodic cleaning, the oxygen gas liberated is only half the volume of hydrogen obtained by cathodic cleaning with the same current density. Whilst it is anodic, the work will repel metallic ions. Smut formed during cathodic cycle can be dislodged during the anodic cleaning. Usually, copper and its alloys should be anodic cleaned for a short time after cathodic cleaning.

Periodic reverse current is presently developed and applied in electrochemical cleaning.

A typical electro-alkaline clean process is:

Solution composition:

- $\text{Na}_2\text{CO}_3$ ............... 30 - 40 gm /l
- NaOH ............... 15 gm /l
- $\text{Na}_3\text{PO}_4$ ............... 10 - 20 gm /l
- Wetting agent appropriate amount
- Complexing agent appropriate amount

Operating condition:

- Current density 3 - 5 A/ dm$^2$
- Temperature 60 - 70 °C
- Time 1-2 min.

Polarity: Anodic for ferrous metal; cathode and short time anodic treatment for the copper base metal.

**2.2.4 Acid dipping**

Acid dipping is usually follows alkaline cleaning to neutralise the alkaline and more importantly, to remove the traces of oxide film on the surface.

1 - 5% HCl or H$_2$SO$_4$, 15 - 45 seconds

**2.2.5 Strike Plating**

The functions of the strike plating are:

- To prevent the surface of the substrate from being attacked by the electrolyte, which would cause poor adhesion;
- To prevent the contamination of the subsequent plating bath;
- To impart good adhesion on subsequent electroplating;
- To activate the surface of the substrate for plating or other coating process.
Some typical strike plating processes are:

**Nickel strike plating**

This process is generally applied to alloy steels prior to the nickel plating.

Solution composition: \( \text{NiCl}_2 \cdot 6\text{H}_2\text{O}: 240 \text{ g/l; HCl: 125m/l} \)

Operating condition:
- Temperature: \( \text{Rt.} \)
- Current density: \( 2 - 4 \text{ A/dm}^2 \)
- Time: \( 1-2 \text{ min.} \)

**Non-Cyanide Copper strike plating (Refer to 4.1)**

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### 3. General Principles of Electroplating

Electroplating is one of the most widely used coating processes which, by means of electrodeposition, a thin metallic coating is applied over the surface of the substrate. The purpose of the coating could be:

i. Withstand oxidation or corrosion;
ii. Resist to abrasion or wear;
iii. Provide an attractive appearance;
iv. Impart special mechanical, electrical, thermal or chemical properties to the surface of the substrate material;
v. Electroforming of moulds / dies or products.

#### 3.1 Electrochemical Reaction

\[
\text{M}^{n+} + \text{n} \text{e}^- \leftrightarrow \text{M}
\]

\[
\text{H}_2\text{O} \leftrightarrow 2\text{H}^+ + 2\text{OH}^- \rightarrow \text{H}_2 \text{(Cathodic)} + \text{O}_2 + \text{H}_2\text{O} \text{(Anodic)}
\]

As soon as a metal salt dissolved in water, it dissociates into electrically charged particles, namely, positively charge metal ions (cations), and negative acid radicals (anions). For example:

\[
\text{CuSO}_4 \leftrightarrow \text{Cu}^{2+} + \text{SO}_4^{2-}
\]

When direct current passes through a metal salt solution between two conductive electrodes, the positive metal ions move towards the cathode, become discharged and deposited on the cathode.

\[
\text{Cu}^{2+} + 2\text{e}^- \rightarrow \text{Cu}
\]

When copper is used for anode; as much copper is dissolved from the anode as it is deposited on the cathode if the current efficiencies are the same.

\[
\text{Cu} \rightarrow \text{Cu}^{2+} + 2\text{e}^-
\]
Consumable anodes (they dissolve) are normally used in order to keep up the concentration of metal ions in the solution to make it stable throughout the electrolysis action. Anodes which do not dissolve are used in some situations such as chromium plating baths (lead alloys), or in some gold plating baths (plasticized titanium). In this later case, the ‘metal’ concentration of the solution is corrected by adding soluble metal compounds to the solution.

### 3.2 The Rate of Electrodeposition

#### 3.2.1 Faraday’s Law

Faraday's Law is the fundamental for all electrolytic processes, which quantifies the amount of metal deposited during electrolysis.

Faraday Law’s indicates that the weight of the metal deposited in an electrolytic process is proportional to the current, plating time, and its chemical equivalent. (Assuming 100% current efficiency)

Thus: \[ W = I \times t \times e \]

Where: \( W \) = grams of metal deposited

\( I \) = current (A)

\( t \) = time (s)

\( e \) = chemical equivalent weight

\( I \times t \) = No. of coulombs of electricity passed

For a given coulomb, the weight of an element discharged is proportional to its chemical equivalent. One Faraday (F) liberates/deposits a gram-equivalent of an element of atomic weight A:

\[ F = \text{Faraday (an electricity to deposit 1 gm equivalent of metal = 96500 coulomb or 26.8 ampere-hour)} \]

\( C \) = coulomb

\( n \) = Valance of the element

\( A \) = Atomic weight

\[ W = \frac{I \times t \times A}{n \times F} \]

<table>
<thead>
<tr>
<th>Metal</th>
<th>Atomic Weight</th>
<th>Valence</th>
<th>Chemical Equivalent</th>
<th>Electrochemical equivalent mg/C</th>
<th>g/Ahr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag⁺</td>
<td>108</td>
<td>1</td>
<td>107.88</td>
<td>1.118</td>
<td>4.024</td>
</tr>
<tr>
<td>Au³⁺</td>
<td>197</td>
<td>3</td>
<td>65.7</td>
<td>0.676</td>
<td>2.436</td>
</tr>
</tbody>
</table>
3.2.2 Cathode Current Efficiency

It is proportional to the total cathode current used in depositing the metal. The portion of the current that is not used for depositing the metal is wasted for liberating hydrogen or other sub-products.

Cathode Current Efficiency = (No. of coulombs depositing metal / Total No. of coulombs passing) X100%

The current efficiency is different for different processes. Acid copper plating is about 99%, bright nickel plating is about 95%, and chromium plating - about 10-20%.

3.2.3 Current Density

Current density is the quantity of current distributes over the entire surface area of the article being plated.
Current density = I / S
I = current
S = surface area
Unit: A / dm², A / ft² or mA /cm²

Current density is an important factor that must be controlled in a definite optimum range to meet the requisite for the metal deposition.

Example- To calculate the time required for plating 1 µm (micron meter) thickness of nickel on an area of 1 dm². (The current density applied is 5 A / dm²) Volume of the 1 pm (0.0001 cm) thickness of nickel is:
10 \times 10 \times 0.0001 = 0.01 \text{ (cm}^3)\\
\text{Mass of nickel deposited} = 0.01 \times 8.907 = 0.08907 \text{ g}\\
= 89.07 \text{ (mg) (Density of the nickel is 8.907g/cm}^3)\\
The mass of nickel deposited in 1 ampere-hour is 1091 mg. So for depositing 89.07 mg of nickel the electrical requisite is:\n\frac{89.07}{1091} = 0.08164 \text{ (ampere-hour)}\\
= 4.898 \text{ (ampere-minute)}\\
The cathode current efficiency of nickel = 95%\\
\text{Therefore, the required ampere-minute} = 4.898 \times 100/95 = 5.156\\

If the current density applied is 5.0 A/dm$^2$, the plating time for depositing 1 micron thickness of Nickel on 1 dm$^2$ is:\n\frac{5.156}{5.0} = 1.03 \text{ (minute)}\\

**3.3 The Rate of Electrodeposition**\\

The rate of electrodeposition varies with different electrolytic processes. Even in a specific plating process it also varies with current density, current efficiency, temperature, agitation, pH, etc.\\

According to the thickness of the deposition required we must control the plating time and choose the optimum current density. However, the thickness of the coating calculated from the surface area, current applied and the plating time is an average value of thickness over the whole surface. The coating thickness varies in different regions of the surface. This is owing to the uneven distribution of current density in the different positions of the surface.\\

Generally, it is a minimum coating thickness on the significant area of the article to be plated where an allowance has to be made. The plating time is also adjusted in order to meet the specified thickness.\\

**3.4 Electrode Potential**\\

A piece of metal immerses in an electrolyte containing its ions will establish a definite electrode potential.\\

**3.4.1 Nernst Equation**\\

The electrode potential can be demonstrated by the Nernst Equation, that is:\n\[\text{E = E}^0 + \frac{RT}{zF} \ln a\]
Where

\[ E: \text{The electrode potential at 25 °C} \]

\[ E^0: \text{Standard electrode potential of a metal in equilibrium with} \]
\[ \text{a solution of its ions at unit molar activity at 25 °C} \]
\[ = \text{molar concentration of the ions multiple activity} \]
\[ \text{coefficient.} \]

The molar activity is correspondent with the molar concentration in vary dilute solutions.

\[ R: \text{gas constant} \]
\[ = 8.315 \text{ J/ °C mol}^{-1} (1 \text{ cal} = 4.184 \text{ J}) \]

\[ T: \text{absolute temperature} \]

\[ Z: \text{valency of metal} \]

\[ a: \text{the activity of the metal iron in the solution} \]
\[ = a_M / a_{M^{n+}}, \text{At 250c} \]

\[ F: \text{the faraday} \]
\[ = 96486 \text{ Coulomb} \]

Assuming that the metal electrode is in a standard thermodynamic state (\( a_M = 1 \))

\[ E = E^0 + 0.059/z \log_{10} a_{M^{n+}} \]

Change of concentration will be the prime factor affecting the electrode potential

Assuming that activity and concentration are equivalent, we may see that diluting a solution shifts the electrode potential to more negative (base) value

<table>
<thead>
<tr>
<th>Concentration</th>
<th>1M</th>
<th>( 10^{-3} \text{M} )</th>
<th>( 10^{-7} \text{M} )</th>
<th>( 10^{-20} \text{M} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potential (volts) E=</td>
<td>( E^0 )</td>
<td>( E^0-0.059 )</td>
<td>( E^0-0.21 )</td>
<td>( E^0-0.59 )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Equilibrium M/M^{n+}</th>
<th>( E^0 )</th>
<th>Equilibrium M/M^{n+}</th>
<th>( E^0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu^{2+} + 2e \rightarrow Cu</td>
<td>+0.34</td>
<td>Ni^{2+} + 2e \rightarrow Ni</td>
<td>-0.25</td>
</tr>
<tr>
<td>H^{+} + e \rightarrow 1/2H_2</td>
<td>0.00</td>
<td>Cr^{3+} + 3e \rightarrow Cr</td>
<td>-0.71</td>
</tr>
<tr>
<td>Zn^{2+} + 2e \rightarrow Zn</td>
<td>-0.76</td>
<td>Au^{+} + e \rightarrow Au</td>
<td>+1.5</td>
</tr>
</tbody>
</table>
3.4.2 Overvoltage and Polarisation

The Nernst Equation is limited to measure electrode potential for the process under the reversible equilibrium i.e. the process with no gross reaction take place. But in most cases electrode reactions are irreversible and that would cause the potential of the anode to become nobler and the cathode potential less noble than their respective static potential calculated from the Nernst Equation. Overvoltage is measure of the degree of this irreversibility and the electrode potential is "polarised".

Thus the electrode potential can be given:

\[
E = E_{\text{rev}} + Y
\]

In which, \(E_{\text{rev}}\) is the electrode potential result of calculation from the Nernst Equation. \(Y\) is the total polarisation.

- \(X_c\) concentration polarisation
- \(Y_a\) activation polarisation
- \(Y_b\) Ohmic polarisation

Knowledge of various types of polarisation in plating systems is useful in eliminating problem. If a metal is plated at a higher concentration, polarisation defect with dull appearance and rough crystalline structure are usually observed because of the short supply of the depositing ions to the cathode surface.

3.4.3 The Effect of Polarisation:

i. Polarisation would increase the bath voltage and decrease the current;

ii. An amount of gases would be released;

iii. A compound or film would be formed on the electrode;

iv. Increasing polarisation would increase the covering power of deposit and would cause the finer deposit. Generally, \(Y_c\) can be decreased by increasing temperature, concentration and agitation of the plating bath.

3.5 Distribution of Deposit

Generally, metal deposited surface is thought to be covered with uniform thickness of coating. In reality, the edge, convex positions where current density is higher, thicker coating compare to the hollow, concave positions of the article would be plated.
The factor to influence distribution of the metal deposit is complex. Factors are:

- The composition, concentration and other properties of the electrolyte;
- The configuration of the article being plated;
- Spacing of anodes;
- Rack of design;
- Operating conditions;
- Types of current applied. (i.e. pulse, reversible or straight d.c.)

### 3.5.1 Covering and Throwing Power

Covering power: denotes the ability of an electrolyte to cover the recess area (low current density) of a component being plated.

Macro-throwing power: it is a measure of ability of an electrolyte to deposit more or less uniform thickness coating over the irregular surface of the article.

Micro-throwing power: it is a measure of ability of an electrolyte to deposit more or less uniform thickness coating in minute (microscopic) irregularities of the surface.

### 3.5.2 To Improve the Distribution of the Metal Deposition

To achieve the uniform thickness coating over the functional areas of the article to be plated is quite significant. Firstly, from the economy viewpoint, it is important to avoid wastage of metal especially the precious metal to meet the minimum required thickness of coating. Secondly, from the technical viewpoint, the thickness would affect the properties of the coating.

In the electroplating process, the distribution of a metal deposit could be improved by the use of proper devices and techniques such as:
i. Stringent control of bath composition to get good throwing power
ii. Use additive agents such as brightener, leveling agents, wetting agents etc.
iii. To minimise the convex and concave irregularities over the significant area of the surface
iv. To adjust the anode spacing and the anode-cathode distance
v. To design and fabricate the proper racks
vi. To use the conducting or insulating screen and auxiliary anodes
vii. To increase the polarisation on the cathode in the proper process
viii. To adjust the operating condition. To control within the optimum range of temperature, current density etc.
ix. Pulse current is usually better than direct current.

4. Copper Plating

4.1 Non-Cyanide Alkaline Copper Plating

Non-cyanide alkaline copper plating is a newly developed non-toxic plating process that is replacing the conventional cyanide alkaline copper plating. This plating process fully complies with the EU Restriction of Hazardous Substances (RoHS) Directive 2002/95/EC as it does not contain Pb, Cd, Hg and Cr\(^{6+}\).

Compared to the conventional plating process, this technology does not have the toxic substances cyanide and pyrophosphate, thus eliminating the potential dangers of cyanide in the workplace and reducing the waste treatment costs for destroying cyanide. Moreover, die cast zinc must be strike-plated first in cyanide or other alkaline baths (e.g. copper pyrophosphate bath), but cannot be plated directly in acid baths; however, it can be plated successively only in a single bath with this new technology, non-cyanide alkaline copper bath can, thereby, take the place of both strike bath and Rochelle salt bath.

Non-cyanide alkaline copper plating has the following advantages:

i) Better throwing power (uniform deposit thickness)
ii) Better adhesion and corrosion resistance
iii) Significant improved resistance to thermal shock.

4.1.1 Electrochemistry

In non-cyanide alkaline copper, the main reaction is shown as follows:

\[ \text{Cu (Complexor)} \rightarrow \text{Cu}^{2+} + \text{Complexor} \]

\[ \text{Cu}^{2+} \rightarrow \text{Cu} \]

4.1.2 Area of Application

i) Pre-plating or undercoating metals
ii) Wire and grounding rods
iii) Printed circuit boards
iv) Decorative coating

4.1.3 Metals Plated

i) Ferrous metals
ii) Brass
iii) Copper
iv) Zincated aluminum
v) Electroless nickel
vi) Die cast zinc

4.1.4 Equipments

<table>
<thead>
<tr>
<th>Item</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank</td>
<td>Rigid PVC or PP made</td>
</tr>
<tr>
<td>Agitation</td>
<td>Vigorous air</td>
</tr>
<tr>
<td>Filtration</td>
<td>Continuous with 5 µm cotton filter</td>
</tr>
<tr>
<td>Heater</td>
<td>Quartz or titanium</td>
</tr>
<tr>
<td>Anode</td>
<td>Phosphorus copper</td>
</tr>
</tbody>
</table>

4.1.5 Operating Conditions

- Temperature: 45-60 °C
- pH: 7.5-8.5
- Current Density: 1-4 A/dm²
- Voltage: 1-6
- Time: 3-10 min.

4.1.6 Solution Composition

<table>
<thead>
<tr>
<th>Item</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper Salt</td>
<td>350-450 ml/L</td>
</tr>
<tr>
<td>Brightener</td>
<td>appropriate</td>
</tr>
</tbody>
</table>

4.2 Acid Copper Plating

4.2.1 Application

Electroforming, electro-refining, manufacture of copper powder, or the under coating applied on the steel parts and zinc diecasting parts that have been strike plated on the alkaline copper plating bath.
4.2.2 Equipment

Tank (with PVC or PE lining), rectifier, electrical and heating controls, copper anodes and bags, anode and cathode bus bars, agitation, heater, filtration, ammeter and timer.

4.2.3 Solution Composition and its Functions

One typical solution composition of the bright acid copper plating bath:

\[
\begin{align*}
\text{CuSO}_4 \cdot 5\text{H}_2\text{O} & \quad 150-250 \text{ g/L} \\
\text{H}_2\text{SO}_4 & \quad 45-110 \text{ g/L} \\
\text{C}_{10}\text{H}_6 (\text{SO}_3\text{Na})_2 & \quad 1-5 \text{ g/L} \\
\text{CS (NH}_2\text{)}_2 & \quad 0.005\text{g/L}
\end{align*}
\]

Copper sulphate CuSO₄ • 5H₂O: It is the primary constituent of the electrolyte and furnishing the copper ion in the solution.

Sulphuric acid H₂SO₄: Its main function is to increase the conductivity.

Brighteners: To improve leveling and throwing power, such as thiourea CS(NH₂)₂, molasses, dextrin, sodium salt of naphthalene disulfonic acid C₁₀H₆(SO₃Na)₂ and so on.

4.2.4 Operating Conditions

Temperature 30 - 40°C
Current density 2 - 4 A / dm²
Voltage 2-4
Agitation moderate

4.2.5 Electrode Reaction

In the acid copper bath, the main reaction on the cathode side is to deposit copper; on the anode side is the dissolution of the copper anode;

\[
\begin{align*}
\text{Cathode:} & \quad \text{Cu}^{2+} + 2\text{e} \rightarrow \text{Cu} \\
\text{Anode:} & \quad \text{Cu} - 2\text{e}^{-} \rightarrow \text{Cu}^{2+}
\end{align*}
\]

5. Nickel Plating

Nickel is the most widely used metal in electroplating. During long exposed to mildly corrosive atmospheres nickel will tarnish - yellow colour, or turn green on severe corrosive environment. Usually a thin layer of chromium/tin cobalt alloy is deposited on nickel plate to prevent tarnishing. Electrodeposits of nickel possess a wide variety of properties, depending on plating bath composition and operating conditions. It can be deposited bright, matt, satin, and black as well as hard, ductile etc.
5.1 Safety Considerations

Nickel and its salts used in electroplating are non-toxic, unless the associated anion is and unless very large amounts are ingested. Skin contact can cause dermatitis (skin itch) in some individuals (The EC countries have banned the use of nickel under coat for jewellery and any other items in constant contact with skins). Vapour of nickel carbonyl Ni (CO)₄ is extremely toxic, much more so than carbon monoxide. Long exposure to nickel containing dusts has been shown to be carcinogenic. To the platers, therefore, the handling of nickel salts is hazardous unless proper precautions are taken.

5.2 Application

There are three major application areas:

5.2.1 Decorative Coating

In which the bright nickel coating is overlapped with bright chromium to produce attractive appearance and protection against corrosion, resistance to wear, and tolerance to high temperature.

5.2.2 Functional Finishes

Where a matt-grey nickel deposit is applied which is generally thicker than the decorative coating. These finishes serve to improve corrosion and wear resistance, to salvage worn or damaged parts or to modify other surface properties.

5.2.3 Electroforming

Where a rather thick nickel deposit is required. The deposited layer is than separated from the mandrel to produce a standalone nicked component.

5.3 Bright Nickel Plating

5.3.1 Equipment

Tank (PE or PVC lining), rectifier, voltmeter and ammeter, current regulator, nickel (nickel square or round) anodes, titanium baskets and bags, anode & cathode busbars, agitator, filter.

5.3.2 Solution Composition and Its Function

Typical Watts bath solution composition:

- $\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$  250-350 g/l
- $\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$  45-60 g/l
- $\text{H}_3\text{BO}_3$  30-40 g/l
- Wetting agent  appropriate
- Brighteners  appropriate
Nickel Sulphate NiSO₄·6H₂O - is the main source of nickel ion. Increasing the nickel content would permit the use of higher current density.

Nickel Chloride NiCl₂·6H₂O - it would improve anode dissolution and increase conductivity; however it would increase the stress of the deposit.

Boric Acid H₃BO₃ - Act as buffing agent to maintain the pH level, help to produce smoother, more ductile deposit.

Anti-pitting or Wetting Agent - Used to improve surface uniformity of deposit mainly by reduce pitting which caused by hydrogen bubbles that cling to the surface of the cathode during plating. One kind of wetting agent is sodium lauryl sulphate CH₃(CH₂)₁₁SO₃Na, 0.01 - 0.5 g/L.

5.3.3 Brighteners

Most of the bright nickel baths utilise two classes of brighteners:

**Class I Brightener**

Used alone could produce certain degree of brightness but unable to produce lustrous deposit as plating continues. This kind of brighteners including naphthalene disulfonic (or trisulfonic) acid, benzene sulphonamide and sulphonamide, saccharine, etc. Relatively high concentrations (15g/l naphthalene polysuphonic acid type of compound) may be used without harmful effects. Class I brighteners do not have a marked effects on the physical properties of deposits as class 11 brighteners, which can only be used at low concentrations.

Often the combined effects of class I and class II used together are much greater than the sum of the effects of each used separately. When used together with class II brighteners, they can effectively use less class 11 brightener to give a superior brightness and to reduce the deleterious effect on mechanical properties caused by class II type brighteners.

The characteristics of class I brighteners are:

Presence of sulfon group or groups (=C-SO₂); Presence of unsaturated carbon linkage in close proximity to the sulfon group.

The brightener can be absorbed on the cathode surface via the unsaturated linkage. The absorption may occur on the growth site, edge points of crystals and dislocations.

**Class II Brightener**

It is used in combination with the class I compounds to obtain lustrous or full bright deposit. It never used alone for brightening due to high tensile stress build up in the coating and other deleterious effects.

Commonly, this kind of brighteners is organic compounds containing
unsaturated group such as:

Formaldehyde HCHO, coumarin C₈H₆OCO, olefinic - C = C - group, ethylene cyanohydrin HOCH₂CH₂CN etc.

A sample of brightener in bright nickel plating:

Naphthalene 1, 3, 6 - trisodium sulphonate - 4 g /l (brightener of the 1st class)

2 - butyne -1, 4 - diol - 0.2 g / l (brightener of the 2nd class)

5.3.4 Leveler

Leveling agents has the ability to hide surface defects and is commonly used to produce semi-bright deposits. Coumarin is the best known. These agents can produce finer grain deposit hence the brightness but cannot produce a full bright deposit. Leveling is the ability to deposit thicker coating in recesses than on the flat part of the surface. Scratches are preferentially filled when levelers are added.

5.3.5 Wetting agent

No brightening system is operational without wetting agent to produce pit-free deposit. Unsuitable wetting agents can result in loss of brightness, lost of leveling and even cause pitting. The ability to lower surface tension is by no means the only criterion of a wetting agent.

5.3.6 Operating Condition

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Room Temperature 50-60°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current density</td>
<td>0.5-10A/dm²</td>
</tr>
<tr>
<td>pH range</td>
<td>3-5.5</td>
</tr>
<tr>
<td>Agitation</td>
<td>Moderate to vigorous</td>
</tr>
</tbody>
</table>

5.4 Maintenance of Nickel Plating Solution

5.4.1 pH Value

During operation, the pH value of the nickel plating solution would tend to rise, so, in order to adjust the pH value, 3 – 5% of dilute H₂SO₄ is generally added at a time with stirring.

To increase the pH value of solution nickel carbonate or nickel hydroxide are preferred than sodium hydroxide.

5.4.2 Solution Composition
The solution constituents should be maintained at the given concentration by regular checking and addition of chemicals.

**5.4.3 Contamination and Cleaning**

The solution must always be kept clean. Cleaning of articles before plating is critical to prevent introducing contaminants into plating baths. The metallic impurities such as iron, lead, copper, zinc etc. would degrade the qualities and appearance of deposit.

Organic impurities would result in stress or brittleness, pitting or poor adhesion on the deposit.

**5.4.4 Removal of Organic impurities and Metallic Contaminants**

To remove the breakdown of organic additives, the solution is transferred to an auxiliary treatment tank and then activated carbon in the concentration of 1-3 g/L is added. The solution is kept with vigorous agitation about 1-2 hours at 50 - 60 °C, allows the carbon to settle then filtered back to the plating bath.

Or the solution is transferred to the treatment tank. Nickel carbonate or nickel hydroxide is added until the pH value reaches 5.2. Then 0.5-1 ml/L of H₂O₂ is added, the solution is agitated and kept at 60 °C about 2 hours. After settling the solution is filtered back to the plating bath.

Dissolved metallic impurities are eliminated by electrolysis carrying out at a low current density 0.01 - 0.2 A/dm² using a corrugated or mesh cathode sheet for several hours or overnight under agitation and plating temperature. After the solution has been purified the addition of chemicals, brighteners, wetting agent should be conducted.

If necessary to remove all the organic substances, e.g. When brighteners are disintegrated, the following treatment may be adopted after activated carbon treatment:

**5.4.5 Treatment with Hydrogen Peroxide and Activated carbon**

Oxidation with 30% H₂O₂ in this treatment the pH value of solution should be raised to 6.

The addition of 0.5 - 3 ml/L of H₂O₂ to the solution should be agitated for more than 30 minutes.

Second carbon treatment and allow solution to settle and filter.

Low current density treatment and filtering until the solution is free from foreign particles.

**5.5 The Thickness of the Nickel Deposit**
In order to estimate the thickness of the nickel deposit, the calculations of the surface area, current density, plating time are required.

The majority of the plating specifications call for a given minimum thickness on the significant surface area.

Commonly, nickel which serves in indoor condition call for a minimum thickness of 5-20 microns and where as in outdoor condition 20-40 microns is needed.

To ensure the specific requisition of thickness, it is necessary to deposit an average thickness that is greater than the specified minimum thickness. The usual practice is to make an initial allowance for about 20-50%. After plating, the plated samples is examined to show the actual thickness produced, the articles can subsequent be plated in the adjusted plating time to ensure the attainment of the specific thickness.

6. **Tin-Cobalt Alloy Plating**

6.1 Introduction

Nowadays tin-cobalt alloy plating is a newly developed process that being adopted by the surface finishing industry to replace chromium plating and provide a decorative plating as same as platinum(Pt.) because of the following advantages:

I. Stable solution control
II. Non-poison and good coverage capability
III. Relatively simple composition

6.2 Area of Application

a) Decorative products  
b) Metal ware  
c) Watch case and clocks  
d) Spectacles frame  
e) Industrial components

6.3 Equipments

<table>
<thead>
<tr>
<th>Component</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank</td>
<td>Rigid PVC or PP made</td>
</tr>
<tr>
<td>Agitation</td>
<td>Cathode rod agitation (1-2 m/min.)</td>
</tr>
<tr>
<td>Filtration</td>
<td>Filter of cartridge type for usual nickel plating</td>
</tr>
<tr>
<td>Heating</td>
<td>Quartz heater, or titanium heat-exchanger</td>
</tr>
<tr>
<td>Anodes</td>
<td>Carbon plate for electrodes</td>
</tr>
<tr>
<td>Power</td>
<td>About 10V, all-wave rectification</td>
</tr>
</tbody>
</table>
6.4 Operating Conditions

Temperature  50-60 °C  
pH  8.5-9.0  
Current Density  0.1-1.0 A/dm²  
Time  1.5 min.

6.5 Solution Composition

Stannous Pyrophosphate  14-20 g/L.  
Cobalt Sulphate  10-20 g/L.  
Brightener  appropriate

6.6 Tin-Cobalt Plating Process

Nickel Plating → Water Rinse → Tin-Cobalt Alloy Plating → Water Rinse → Post treatment → Water Rinse → Drying

7. Anodising and Dyeing of Aluminium

The basic reaction in anodising is the conversion of the aluminium surface to aluminium oxide while the part is made anode in an electrolytic bath. Anodic oxidation of aluminium provides a hard, protective and decorative aluminium oxide film. The process is used for:

Decorative finishing - The micro-porous oxide film formed provides wear-resistant and protective finish. It can also be dyed to give a wide range of attractive colours.

Hard finish - A thicker (hence harder) oxide film can be formed for architectural and engineering applications. If sufficiently thick coating (over 30µm) is formed, it become electrically insulating of up to 300V.

7.1 Classification

According to the types of electrolytes adopted, anodising processes can be classified into different classes, from which different properties of oxide films are produced.

<table>
<thead>
<tr>
<th>Electrolyte</th>
<th>Operating condition</th>
<th>Properties of oxide film</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulphuric acid 10-15%</td>
<td>1-2 A/dm² , 12-18V</td>
<td>Transparent to grey colour rather hard and low ductility</td>
</tr>
<tr>
<td>Chromic acid 10%</td>
<td>0.3 A/dm² , 45-56 V</td>
<td>Light to dark grey colour, more ductile</td>
</tr>
<tr>
<td>Chemical</td>
<td>Current Density</td>
<td>Voltage</td>
</tr>
<tr>
<td>----------</td>
<td>----------------</td>
<td>---------</td>
</tr>
<tr>
<td>Oxalic acid</td>
<td>1-2 A/dm², 65 V</td>
<td>Creamy colour</td>
</tr>
<tr>
<td>Phosphoric acid</td>
<td>1 A/dm², 30-60 V</td>
<td>Transparent to bluish colour</td>
</tr>
</tbody>
</table>

The processes using sulphuric acid or chromic acid are the most widely applied methods commercially:

A. Sulphuric acid process provides a hard and transparent film, and can be easily dyed to various colours but the different alloys would result in variation of opaqueness. Pure aluminium or aluminium-magnesium alloys would produce colourless and bright oxide film, aluminium-silicon-copper alloys of low contents of alloy elements may produce undesirable opaque to dull grey colours. Aluminium alloys with high silicon, copper, magnesium etc. are not suitable for anodising.

B. Chromic acid process would produce darker colour of oxide film, and it is more ductile to permit bending and folding. It is widely used for anodising aircraft parts particularly where entrapping areas from blind holds and overlaps are present. For the reason that entrapped chromic acid will not, as sulphuric acid will do attack the aluminium.

### 7.2 Sulphuric Acid Anodising Process

#### 7.2.1 Principle

The parts to be anodised are made anodic during treatment, and aluminium oxide would be formed. The main reactions include electrolysis of water and formation of oxide film.

\[
\begin{align*}
2H_2O & \rightarrow 2H_2 + O_2 \\
4Al + 3O_2 & \rightarrow 2Al_2O_3 \\
Al & \rightarrow Al^{3+} \\
Al_2O_3 + 6H^+ & \rightarrow 2Al^{3+} + 3H_2O
\end{align*}
\]

![Figure 3-Structure of oxide film](image-url)
The oxide film is formed on the anode, but on the other side the sulphuric acid has a solvent action on the aluminium oxide and aluminium metal. It corrodes the film so that a porous structure of oxide is formed. The size of the pore or cell of the oxide film depends on the solution concentration, temperature and current density. Using a more concentrated acid and higher temperature would give a larger size pore suitable for dyeing. Conversely, using a lower temperature would give smaller size pores and harder film suitable for architectural and engineering usage. When dyeing, the porous structure of oxide film would absorb the dyestuff to produce the desired colour.

In order to close up the porous oxide coating the articles must go through a sealing process; generally, hot water or hot cobalt-nickel acetate solution are commonly used as sealing agents. After sealed in the hot or boiling water the amorphous alumina (Al₂O₃) of the cell is converted to boehmite (Al₂O₃·H₂O) of greater volume; therefore, the smaller pore after sealing will be closed up.

7.2.2 Equipment

Tank (PVC lining), rectifier and electrical controller, thermostat, chiller or refrigerator, anode and cathode bars, lead cathodes, continuous filtration and agitation.

7.2.3 Solution Composition and Operating Condition

<table>
<thead>
<tr>
<th>Solution composition:</th>
<th>H₂SO₄</th>
<th>10-15%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H₂C₂O₄·2H₂O₄</td>
<td>2-5%</td>
</tr>
<tr>
<td>Current density</td>
<td>0.5-2.5A/dm²</td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>15-20 °C</td>
<td></td>
</tr>
</tbody>
</table>

To obtain a thicker (harder and high wear) film, the temperature should be controlled in a lower range.

For semi-hard anodising, temperature at 10 - 15 °C; for hard anodising, temperature at +5°C to -5°C.

7.2.4 Thickness Specification

For the most decorative application, the oxide film thickness is about 5 -10µm; and for architectural used the oxide film should not be less than 25 µm; for hard anodising the oxide film thickness range is 25-125 µm.

7.2.5 Rate of Oxide Formation

Normally a current density of 1.5 A/dm² and in a period of 2.4 minutes would produce 1micron thickness of oxide film.

The thickness of the oxide film for a given electrolyte can be calculated by the formula:

\[ \sigma = Klt \]
σ  The thickness in µm
K  Anodising coefficient, 0.25 -0.36, usually 0.3 is used.
    It decreases when the concentration and temperature is increased.
I  Current density A/dm²
T  Time in minutes

Whatever if a dark colour is required in the subsequent dyeing process anodising time should be longer, generally 60 minutes is required.

**7.2.6 Dyeing of Anodised Oxide Film**

Different colour dyestuffs are available commercially. When dyeing, immerse the article into the aqueous dyestuff solution.

| Dyestuff solution concentration | 1 - 5 g/1 |
| Temperature                    | 30 - 40 °C |
| pH                            | 5 - 7      |
| Time                          | 1- 5 minutes |
| Agitation                     | moderate   |

**7.2.7 Sealing anodic coating**

After dyeing, the pores in the film must be sealed to block the dyestuff from running out and to prevent attack by contaminates and corrosive substance in the atmosphere.

Sealing usually involves subjecting the anodic coating to a hot aqueous solution, which causes hydration of the coating:

\[
\text{Al}_2\text{O}_3 + \text{H}_2\text{O} \rightarrow \text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}
\]

The resistance of anodic coating to staining and corrosion is affected by the absorption of foreign substance into the coating. Therefore, sealing treatments usually are employed immediately after anodising. Improperly sealed coatings can account for pitting attack, colour change, and mottling.

The most widely used sealant employs water although only high-purity water is recommended. Sealing temperature is important and should be 98-100 °C. Sealing time should not be shorter than 10 min for thin (2.5 µm) decorative coating and can be as long as 60 min for thicker (25 µm) coatings

**7.3 Safety**

**Electrical hazards**

As the voltage used in anodising tends to be higher, care must be taken during manual handling. Interlocking switches, warning devices and fast acting overload devices and leakage breakers are to be installed.

**Chemical hazards**
Sulphuric acid (H₂SO₄) is highly corrosive. Thus an apron, rubber gloves and face shield should be worn when handling the sulphuric acid.

8. Electroforming

8.1 Introduction

Electrodeposition is to deposit an adherent metallic coating on an article by electrochemical means. Electroforming is the production or reproduction of articles by electrodeposition upon a mandrel or mould that is subsequently separated from the deposit.

Electroforming is a rapidly expanding technology owns much of the high precision obtainable on intricate and complex shaped articles that could be difficult if not possible by other means. For example, the stamper for phonograph-records, electrotype printing plates, moulds for CDs and laser discs are all made by electroforming.

Many of the principal pieces of equipment and techniques employed in electroforming, e.g. mandrels metalizing or passivation techniques, electrolytic tanks, filters, pumps and sources and control of direct current or pulse current, are the same as used in electroplating.

As a production process electroforming has the following advantages:

i) Simplicity
ii) Fidelity
iii) Reproducibility for any type of surface
iv) Ease of replication

8.1.1 Typical properties of electroformed metals

<table>
<thead>
<tr>
<th>Metal</th>
<th>Mech. properties</th>
<th>Bath</th>
<th>Mech. Properties electroformed</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>34000 psi</td>
<td>45% E</td>
<td>20000-68000 psi 15-40%E 40-85VHN Internal stress</td>
<td>Bath composition, additional agents and operational conditions could influence properties</td>
</tr>
<tr>
<td></td>
<td>45VHN</td>
<td>Sulphate</td>
<td>400-2000 psi</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sulphate + Phenosulphonic acid</td>
<td>69000-90000 psi 1-20% E 80-180 VHN</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sulphate + molasses and thiourea</td>
<td>80000 psi 3% E, 170 VHN</td>
<td></td>
</tr>
</tbody>
</table>
### 8.1.2 Applications

Typical applications are as follows:

1) Manufacturing of duplicating plates:
   - Electrotype, phonograph record masters, embossing plates, graining plates.

2) Thin-walled sections:
   - Foils and sheets, hypodermic needles, fine mesh screens, seamless tubing.

3) Precision components
   - Moulds and dies, denture moulds, paint-spray masks.

4) Parts difficult or impossible to make otherwise
   - Radar wave guides, linear electron accelerator structures, surface roughness gauges, reflectors, musical instrument components.

### 8.1.3 Advantages

1) Varying the bath composition and operational conditions may vary the mechanical properties of an electrodeposited metal. In many instances properties can only be obtained by electrodeposition.

2) Parts can be produced in quantity with very high dimensional accuracy, being limited only by the accuracy in machining the mandrel. This can be illustrated in the electroforming of record stampers, since faithful reproduction of the recorded sound depends on precision modulations in the sound track itself, which is only one thousandth of an inch.

3) Any desired surface textures could be reproduced. For instance, in a microgroove phonograph record, the smallest modulation to reproduce for high fidelity is about half a millionth of an inch. Also, machine surfaces of any standard; highly polished (mirror finishes), the graining of leather, the texture of skin etc.

4) There is virtually no limit to the size of the object that can be electroformed. i.e. hypodermic needles, foil of 0.0001 inch thick, 400 mesh screen or bulky objects of complicated geometry weighing several hundred pounds.

### 8.1.4 Disadvantages
Cost is relatively high:
1) The deposition rate in electroforming is relatively slow, often being measured in days.
2) There are some limitations in design. Sharp angles, deep and narrow recesses, sudden changes in cross sections or wall thickness etc. should be avoided.
3) Because of the excellent reproducibility, scratches and imperfections in the electroformed master will appear in the products.

8.1.5 Electroforming with Copper/Nickel

Copper is widely used. It is relatively inexpensive, deposition rate is high and the electroformed component is low in internal stress. Nickel can be deposited over a wide range of properties than any other metal and the effects of bath composition, additives and operational conditions are more fully studied.

8.1.6 Stress in deposits

It is a well-known fact that electrodeposits generally are highly stressed. The internal stresses may cause tight grip of the mandrel, distortion of the electroformed article, bucking, blistering. During the process the stress level may cause the deposit to curl up at the edges or to exfoliate.

Copper deposit has a lower stress when compared with nickel. Depending on bath type and operational conditions, some of the nickel deposits have stresses so high that rupture may occur during the process. Thus, internal stress is one of the main concerns in electroforming and for nickel; a bath that results of lower stresses is desired (i.e. containing stress reducing agents).

8.2 Nickel Electroforming

Nickel Sulphamate and Watts Nickel are commonly used:

<table>
<thead>
<tr>
<th></th>
<th>Watts Nickel (g/L)</th>
<th>Nickel Sulphamate (g/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NiSO₄·6H₂O</td>
<td>225-300</td>
<td></td>
</tr>
<tr>
<td>Ni(SO₃NH₂)₂</td>
<td></td>
<td>315-450</td>
</tr>
<tr>
<td>NiCl₂·6H₂O</td>
<td>37.5-52.5</td>
<td>0-22.5</td>
</tr>
<tr>
<td>H₂BO₃</td>
<td>30-45</td>
<td>20-45</td>
</tr>
<tr>
<td>Temperature, °C</td>
<td>44-66</td>
<td>32-60</td>
</tr>
<tr>
<td>Agitation</td>
<td>Air or mechanical</td>
<td>Air or mechanical</td>
</tr>
<tr>
<td>Current density, A/dm²</td>
<td>3-11</td>
<td>0.5-32</td>
</tr>
<tr>
<td>pH</td>
<td>3-4.2</td>
<td>3.5-4.5</td>
</tr>
</tbody>
</table>
As can be seen nickel sulphamate is preferred formulation for electroforming as it can be deposited at higher rate with much reduced internal stresses in the electroformed items. Record stampers, plastics moulds, intricate shaped filters, meshes; screens etc. which cannot be produced in any other way are often formed with nickel sulphamate formulations.

8.3 Electroforming in Nickel Sulphamate Bath

Nickel Sulphamate based plating solutions are employed wherever high speed, low stress, heavy nickel plating is required. The solutions are used for salvage of wore out or damaged parts and, for the production of gramophone masters and stampers, moulds for plastics and rubber, filters, meshes and screens for the chemical, food, electronic and aircraft industries and a whole range of articles that cannot be produced in any other way.

In the printing industry nickel plating is employed for the facing of stereo-types and copper half tone plates in order to provide a hard wear-resistant surface and thus permit a very considerable increase in the number of impressions.

Electro-types-duplicates of printing plates are now generally electroformed in nickel rather than copper.

8.3.1 Solution Composition

<table>
<thead>
<tr>
<th>Component</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel Sulphamate Concentrate</td>
<td>sp. gr. 1.47 -- 500 ml/l</td>
</tr>
<tr>
<td>Boric acid</td>
<td>---------------</td>
</tr>
<tr>
<td>Nickel Chloride</td>
<td>----------------</td>
</tr>
</tbody>
</table>

When used for electroforming at high current densities it may be advisable to add a wetting agent to prevent pitting. Anti-pit liquid is recommended for this purpose. An initial addition of up to 0.5 ml/L should be made, further small quantities being added from time to time as required.

8.3.2 Solution Preparation

Fill the tank 1/4 full with warm deionized water
Add the measured amount Nickel sulphamate and then heat up to 55-66 °C
Add the required amount of boric acid and nickel chloride
Adjusting pH to 4.2 using sulphamic acid or nickel carbonate
Before use: Filter through with activated carbon and Electroplating at 0.5 A/dm²
for a period calculated using 10 ampere-hour/Liter.

### 8.3.3 Operating Condition

#### Cathode Current Density

2 to 16 amp/dm² For the nickel facing of silvered plastics use 1 amp/dm² for 15 minutes increasing to 5.5 amp/dm² for minutes.

For nickel facing printing stereos, 2.2 to 6.5 amp/dm² for 10 to 15 minutes. Higher current densities of up to 16 amp/dm² may be employed for the production of heavy deposits, e.g. for electroforming.

#### pH Value

3.9 to 4.2. Unlike other nickel solutions the pH is lowered by means of sulphamic acid.

#### Temperature

The temperature at 40°C (100°F) for the plating of plastic mandrels or low melting point alloys. 55 to 60°C (130 to 140°F) for general purpose nickel plating and electroforming. Do not let the temperature rise above 75°C (167°F) or hydrolysis of the nickel sulphamate will occur.

#### Agitation

Vigorous air agitation is essential, especially when plating at high current densities.

### 8.3.4 Solution Maintenance

The density of the nickel sulphamate solution should be 30°Be (52° Tw). If the density falls an addition of Nickel Sulphamate Concentrate should be made to the extent of 9 ml/L for each 1° Tw deficiency in density, 16 ml/L for each 1° Be deficiency.

#### Purification

Where the Nickel Sulphamate solution is used for the production of electroforms, it is essential to have continuous filtration through activated carbon and periodically plating-out at low current density. This will maintain the internal stress at low value and prevent distortion of the electroformed parts after removal from the mandrels.

Pumping the solution from the bath using a filtering pump (with activated carbon filter) into low current density treatment bath at a higher level than the plating bath. The solution then returns via an overflow pipe. This treatment bath may be 10 or 20 per cent the capacity of the main bath and the total volume of
solution should be circulated though it 2 to 5 time per hour. It should be plated out at a current density of between 0.1 - 0.5 amp/dm². The cathodes should be removed regularly and cleaned.

8.3.5 Nickel Anodes

Nickel anodes for electroplating are available in the form of the bar of oval section, which is made by casting, rolling, or extruding carbon-containing or depolarised nickel. Carbon bearing anodes are re-commended for use in 'bright' solutions operated at pH below 5.0.

Depolarised anodes may be used in 'dull' solutions operated over the whole range of pH

Used commercially. Nickel anodes are also made by fixing hooks or clamps to strips of electrolytic cathode sheets, or by putting pieces sheared from such sheets, or nickel pellets, into titanium mesh basket. A new form of nickel anode having particularly good dissolution characteristics is available in pieces 1 in. x 1 in. x 1/2 in. (2.5 cm x 2.5 cm x 1.2 cm). All anodes require the use of bags to prevent the normal anode sludge from entering the solution. These bags, are normally of woven polypropylene, TERYLENE*, or cotton twill.

8.3.6 Rate of Electrodeposition

The deposition rate of Nickel in Sulphamate Solution is approximately listed:

<table>
<thead>
<tr>
<th>Temperature °C</th>
<th>35</th>
<th>40</th>
<th>45</th>
<th>50</th>
<th>60</th>
</tr>
</thead>
<tbody>
<tr>
<td>C.D. A/dm²</td>
<td>1.1</td>
<td>2.7</td>
<td>4.3</td>
<td>8.1</td>
<td>17.8</td>
</tr>
<tr>
<td>Plating rate (Approx.) µm/h</td>
<td>12</td>
<td>31</td>
<td>50</td>
<td>94</td>
<td>296</td>
</tr>
</tbody>
</table>

8.3.7 Mandrel Preparation and Separation

All mandrel surfaces must be treated with a separating film to prevent strong adherence of the electrodepots. This film must be thin enough and sufficiently conductive to allow formation of a sound, faithful replica of the surface.

8.3.8 Stainless Steel or Electrodeposited Chromium Mandrels

Such mandrels are prepared easily for electroforming. A suggested procedure follows:

a. If heavily coated with grease or oil, degrease in chlorinated solvent.
b. Rinse in water.
c. Anodic treatment in a (45g/1) solution of trisodium phosphate, opened at 140 to 180°F (60 to 82°C) for 1 minute at 5.4 amps per sq. dm.
d. Rinse in water at 100°F (38°C). If surface is not uniformly wetted, repeat step "c".
8.3.9 Plastics Mandrels

Plastic mandrel must be made conductive before electroforming by the application of a silver, nickel, or copper film. This also the way for electroplating of plastic.

A suggested procedure for preparing non-metallic materials to receive the silver film is as follows:

a) Remove grease from film, finger marks, etc. by using mild cleaners. In large-scale production operations, as in electrotype manufacture using vinyl moulds, scrubbing with a soft brush and magnesium oxide slurry is an effective aid to the cleaning operation.

b) Rinse thoroughly with running water; spraying is preferred.

c) Sensitising. This treatment is probably the most important and critical step in silvering any non-conductive surface for electrodeposition. The sensitising solution is sprayed or dipped until a continuous film is obtained. A typical sensitising solution has the following composition:
   
   | Stannous chloride | 2.5 to 10 g/l |
   | Hydrochloric acid (35%) | 40 cc/l |

   d) Remove excess sensitising solution and rinsing thoroughly with running water prior to the application of the silver film.

e) Apply silver film by the chemical reduction of silver nitrate immediately after sensitising and rinsing. The silver and reducing solutions generally are applied simultaneously as a spray by means of a double-nozzle gun, which mixes the reducing solution with the silver nitrate. Among the numerous solutions used for this purpose, the commonly applied one is detailed below:

   Silver Solution:
   
   | Silver nitrate | 55 to 60 g /l |
   | Ammonium hydroxide (29%) | 60 to 75 cc /l |

   Reducing solution:
   
   | Dextrose | 100 g /l |
   | Formaldehyde (40% by vol) | 65 cc /l |

   A concentrated ammonium hydroxide is added slowly to the silver nitrate solution, a precipitate is formed, which slowly dissolves when excess amount of ammonium hydroxide is added. The excess free ammonia is essential to keep the solution ammoniac and prevent silver from precipitating from the solution. A number of proprietary silver solutions and reducing solutions are available.

9. Plating on Plastics

The use of plastics materials have been increased many folds during the past decades. Plastics have replaced substantial amounts of metals. In particular, high strength and rigid plastics are commercially viable to replace zinc-based die-
castings for industrial, office, and domestic applications. Plastics are lightweight, excellent corrosion resistance and in many cases may offer greater flexibility in design. Metallic appearance is more attractive and much desired by customers, and in some cases it is necessary to protect the plastics from degradation by ultra-violet light.

To electroplate on any non-metallic object, the first step is to make the surface conductive; when this is accomplished, the subsequent steps in electroplating on the object dose not differ substantially for any other types of electroplating processes.

### 9.1 Pre-plating cycle

<table>
<thead>
<tr>
<th>Process</th>
<th>Description</th>
<th>Operating Condition</th>
<th>Agitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acidic Degreasing</td>
<td>This is a mould release process which used to remove dirt, including dust, stains on the substrate before any other treatment.</td>
<td>Cleaner: 40-60ml/L H₂SO₄: 40-60ml/L Temp.: 25-40 °C Time: 0.5 - 5min.</td>
<td>Mechanical</td>
</tr>
<tr>
<td>Chemical Roughening</td>
<td>Applicable ABS, PP etc. To obtain adhesion for subsequent metal deposition by chemical reaction. Chemical etching can be replaced by mechanical means. For good coating adhesion, under etching and over etching should be avoided. Under etching may lead to skip plating and over etching may result in surface degradation causing poor adhesion and blistering. There are many proprietaries etching agents available. The etching solution is make up of chromic agents. During etching $\text{Cr}^{6+} + 3\text{e}^{-} \rightarrow \text{Cr}^{3+}$ Etching away the Butadiene roughens the surface of ABS (Acrylenitrile – Butadiene – Styrene. This gives a porous surface that is able to retain the catalytic substances during Sensitising.</td>
<td>Chromic acid (CrO₃): 75g/l H₂SO₄: 250ml/l Temp.: 30 – 60 °C Time: 3 – 10min</td>
<td>Mechanical</td>
</tr>
</tbody>
</table>
The etched surface is neutralized in a solution, it is rinsed and followed by acid dip.

**Neutralization**
When used after the rinses following chromic acid etch, the Neutralizer reduces residual hexavalent chromium and prepares the etched plastic surface for catalysis.

- **HCl:** 8-12% by volume
- **Neutralizer:** 2 - 3% by volume
- **Temp.:** 48.9-60 °C
- **Time:** 2 - 4min

**Sensitising** *(Catalyst pre-dip)*
This is the absorption of a reducing agent on the surface, a kind of colloidal substance, to facilitate the adsorption of a catalyst in the next step of treatment. The commonly used sensitizer, or reducing agent, is stannous chloride.

SnCl₂ + H₂O → Sn(OH)Cl + H⁺ + Cl⁻ ------- (1)
SnCl₂ + 2H₂O → Sn(OH)₂ + 2H⁺ + 2Cl⁻ --- (2)

Sn(OH)Cl in (1) and Sn(OH)₂ in (2) combine to produce a slightly water soluble colloid of Sn(OH)Cl·Sn(OH)₂ at the roughened surface.

- **SnCl₂:** 20 g/l
- **HCl:** 40ml/l
- **pH:** 0.5-1.9
- **Temp.:** 20 - 36°C
- **Time:** 1 - 5min

**Catalytic treatment** *(nucleation)*
To precipitate a precious metal element on the surface. Palladium being the most common. The precipitate acts as the catalyst for subsequent electroless copper, silver or nickel deposition.

- **Solution A:**
  - PdCl₂ 1.0g/L
  - SnCl₂·2H₂O 2.5g/L
  - SnCl₃·3H₂O 7g/L
  - Dissolve in 100ml of HCl

- **Solution B:**
  - Na₂SnO₃·H₂O 75g/L
  - Dissolve in 200ml of HCl

- **Prior to use,** mix sol. A and B and dilute 200 times with distilled water.

- **pH:** 3.5-4.5
- **Temp.:** 20 - 35°C
- **Time:** 1-5 min.
A colloidal \([\text{Pdm}_n \text{Sn}^{2+} \cdot 2(n-x)\text{Cl} \cdot 2x\text{Cl}^{-}]\) is formed from the above reaction. The values of \(m\), \(n\) and \(x\) are affected by concentrations of Pd, Sn and HCl.

**Accelerator**

After rinse with distilled water, the article is immersed into a solution (accelerator). Where the outer layer of the tin ion colloid etc. is dissolved exposing the Pd particles at the surface.

\[
\text{Sn(OH)}_2 + \text{HCl} \rightarrow \text{Sn}^{2+} + 2\text{Cl}^{-} + \text{H}_2\text{O}
\]

**Electroless Nickel Deposition**

Electroless Nickel provides an adherent conductive coating on plastic substrates that serves as a protection for the Electroless copper layer.

**Mechanical**

**Electroless Copper Deposition**

Prior to use add HCHO (35%) 10-25 ml/L; Pd at the surface act as the catalyst.

\[
[Cu(\text{H}_2\text{O}_4\text{H}_4\text{O}_6)]^{4-} + \text{HCHO} \rightarrow \text{Cu} + (\text{H}_2\text{O}_4\text{H}_4\text{O}_6)^{2-} + \text{CO}_2 + \text{H}_2\text{O}
\]

**Mechanical/ Air**

### 9.2 Plate through holes (PTH) of print circuit board (PCB)

#### 9.2.1 PCB materials:

Epoxy-impregnated fiberglass cloth, (e.g. G-10, FR-4) is normally used for double sided and multi-layer computer and industrial electronics application.

#### 9.2.2 PTH of PCB:

The purpose of an electroless copper plating process is to render enough conductivity to the drilled through-holes and vias of a circuit board to electroplate those surfaces. Once plated, the hole wall surfaces then permit electrical connection form one side of the circuit board to the other side, and/or form layer to layer in a multilayer board.
### 9.2.3 Process of PTH

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Description</th>
<th>Operational Condition</th>
<th>Agitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desmear</td>
<td>Cleans and activates the hole-wall.</td>
<td>Temp.: 60 – 80°C Time: 2-10 min.</td>
<td>Mechanical</td>
</tr>
<tr>
<td>Neutralisation</td>
<td>Remove manganese residues and enhance coverage on hole-wall</td>
<td>Temp.: 50 – 55°C Time: 4-6 min.</td>
<td>Mechanical</td>
</tr>
<tr>
<td>Sensitising &amp; Catalytic treatment</td>
<td>This is the absorption of a reducing agent on the surface, a kind of colloidal substance, to facilitate the adsorption of a catalyst in the next step of treatment. Palladium being the most common. The precipitate acts as the catalyst for subsequent electroless copper.</td>
<td>Temp.: 20 - 36°C Time: 1- 5min.</td>
<td>Mechanical</td>
</tr>
<tr>
<td>Acceleration</td>
<td>The outer layer of the tin ion colloid etc. is dissolved exposing the Pd particles at the surface.</td>
<td>Temp.: 20 – 30 ° C Time: 1- 3 min.</td>
<td>Mechanical</td>
</tr>
<tr>
<td>Electroless deposition</td>
<td>Electroless copper provides an adherent conductive copper layer on hole-wall.</td>
<td>pH: 11-12.5 Temp.: 15-35°C Time: 10-20 min.</td>
<td>Mechanical/Air</td>
</tr>
<tr>
<td>Acid copper electroplating</td>
<td>Increase thickness of the copper layer</td>
<td>Temp.: 20-25°C Time: 10-20 min.</td>
<td>Mechanical/Air</td>
</tr>
<tr>
<td>Post-treatment</td>
<td>Antitarnish of copper layer is formed and conduce following process</td>
<td>Temp.: 20-25°C Time: 0.5-1 min</td>
<td>Mechanical</td>
</tr>
</tbody>
</table>

### 9.2.4 Troubleshooting of PTH
Problems | Cause
---|---
Partial voids refers to areas on the hole wall that are not covered by copper | Hole wall damaged in drilling
Not enough desmear and hole cleaning
Unsuitable operating conditions of electroless copper baths
Poor rinsing

Hole wall pull away | Not enough desmear
Excessive conditioning
Unsuitable operating conditions of electroless copper baths

Inner connective defect | Not enough acceleration
Rinse too long
Unsuitable operating conditions of electroless copper baths

9.3 Safety

Chemical hazards

Chromic acid and sulphuric acid are highly corrosive and hexavalent chromium compounds are toxic and carcinogenic. For this reason, chromic acid oxidation is not used on an industrial scale. Thus an apron, rubber gloves and face shield should be worn when handling the acid solutions.

The standard first aid treatment for acid spills on the skin is irrigation with large quantities of water. Contaminated clothing is removed immediately and the underlying skin washed thoroughly.

10. Electrophoretic Coating Process

Electrophoretic coating process is a clear or coloured paint (lacquer) applied over metals by electrodeposition. The parts are firstly cleaned and rinsed in deionized water, and then transferred to the aqueous electrophoretic paint emulsion bath; a d. c. current is allowed to pass through the emulsion and the parts.

The electrostatic charged lacquer particles are attracted to the surfaces of the parts under the influence of the electric current. The paint particles adhere to the surfaces and build up to a certain thickness and become electrically insulating
thus no further addition of particles is possible, resulting in a perfectly level coating even in the recessed areas of complex shaped articles. The parts are then removed from the bath and baked in oven.

10.1 Principle

In electroplating, metal ions are attracted to the cathode and become discharged.

\[ M^+ + ne^- \rightarrow M \]

In electrophoresis charged particles attracted to move to the electrode of opposite sign under electrostatic force where no discharge takes place but the particles accumulate. The particles (sols or colloids or others) have a net surface charge due to absorption of ions from solution, so large particles can migrate under a few adsorbed ions. The rate of deposition is many times greater than Faraday's law can predict. The particles are essentially covalent and become charged in the presence of absorbed ions. The particles may be positively or negatively charged depending on the absorbed ions.

For example, Fe$_3$O$_4$ can be positively charged or negatively charge in the presence of the trace ions:

\[ [\text{Fe}_3\text{O}_4 \cdot x\text{H}_2\text{O}]\text{Fe}^{3+} \text{ and } 3\text{Cl}^{-} \text{ or } [\text{Fe}_3\text{O}_4 \cdot x\text{H}_2\text{O}]\text{OH}^{-} \text{ and } \text{Na}^{+} \]

As the film is deposited, Endo-osmosis effectively forces out the liquid phase (water and minor additions which are present e.g., organic solvents and others act as suspending medium), to leave a film that may approach 95% solids. As the film thickness increases, its electrical resistance also increases, until it virtually stifles further deposition. The film thickness is normally 5 - 30 µm for consumer products. The deposition process is progressively shifted to less accessible areas. The deposited film contains little soluble ingredients except paint solids, is a compact and adherent coating which, even not subjected to curing by stove heating, will stand reasonable handling, although this should be avoided.

10.2 Advantages

In comparison with other painting methods, the electrophoretic coating has the following advantages:

1. A uniform film is deposited on all parts of the article with excellent coverage on recess, sharp edges with absence of runs and sags from holes and overlaps.
2. No shielding effect, boxes and complex shaped articles can be full covered.
3. No wastage of paint.

Nowadays, water based polymers are most commonly used, it offers certain advantages over solvent based system, particularly with respect to harmful vapor, fire risk, costs, ease of cleaning and maintaining, readily applied to wet surfaces.
The initial applied current is relatively high; it quickly drops to a low value once a steady state of deposition is established. The film grows faster, becoming more electrical resistive.

After electrophoresis, the coating is heated to dry out traces of suspension and cure the particles to form a mechanically strong film, which can sustain flexing.

**10.3 Pretreatment**

In electrophoresis or any other surface finishing process, the ultimate success lays on the care taken in prior cleaning. The adhesion of coating to metal has been extensively studied and the complexity of the bonding mechanism is still not fully understood. Furthermore, the study of boundary conditions shown that presence of traces of gaseous matters or other impurities during the coating process can greatly impair adhesion.

The most commonly used surface preparation for painting is mechanical roughening which provides some degree of mechanical keying.

Chemical treatment is also used to produce an etched micro-roughen surface or to produce a micro-porous film which act as a primer for subsequent painting, typical examples are phosphating and chromating. Prior to any chemical or electrochemical treatment, the metal surface must be clean and free from grease, scale and rust. As mention above the commonly use process is Ultrasonic cleaning. The sequences of cleaning operation are detailed as follows.

**10.4 Coating Process**

The article is attached to one electrode (anode or cathode) and another is a non-consumable electrode made of stainless or any suitable metal, a D.C. current is applied (The following figure shown the basic set up of the system) for a period from 1 - 3 minutes, after rinsing in a still tank is washed with deionized water.
### Operating Conditions

<table>
<thead>
<tr>
<th>Operating Condition</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Voltage and Current</strong></td>
<td>When operating at constant voltage, the initial current density is higher, as the process proceeds, current falls quickly owing to the growth of the insulating coating.</td>
</tr>
<tr>
<td><strong>Time</strong></td>
<td>Depending on the coating thickness required. Depending on coating system, after a certain period, an optimum coating thickness is attained, due to the increased resistance of the coating, the current is decreased to a point that electrolysis effectively ceased.</td>
</tr>
<tr>
<td><strong>Temp.</strong></td>
<td>In a continuous production, it is essential to maintain a constant temperature. At higher temperatures conductivity, pH, and viscosity may be affected, dissociation of the colloidal or sol may occur.</td>
</tr>
<tr>
<td><strong>Agitation</strong></td>
<td>Keep the solution stirred to maintain uniform viscosity and prevent settlement of the paint particles. A gentle solution movement is sufficient.</td>
</tr>
<tr>
<td><strong>pH</strong></td>
<td>Higher pH may arise from the traces of alkali cleaning solution, causes precipitation. Lower pH may due to drag in acids. If the low pH is due to normal acid built up, no permanent harm is done to the bath.</td>
</tr>
<tr>
<td><strong>Filtration and ultra-Filtration</strong></td>
<td>To remove solid impurities by filtration. And filtration per to remove metal ions cations and anions (chlorides, sulphates, alcalis etc.) and, some of the water by ultra-filtering with special ion exchange cartridge. The emulsions are retained during ultra-filtration.</td>
</tr>
</tbody>
</table>
10.5 Safety

Electrical hazards

As the voltage used in electrophoresis tends to be higher, care must be taken during manual handling. Interlocking switches, warning devices and fast acting overload devices and leakage breakers are to be installed.

Fumes

Adequate ventilation should be provided to ensure that all toxic fumes are readily extracted. Tank additions may include ammonium hydroxide, amine, and solvent, the vapour generated are harmful if inhaled.

Fire risk

The electrophoresic tank depending on the system may contain inflammable materials.

11. Electroless Nickel Deposition

Electroless nickel deposition (EN) is used to deposit nickel without the use of an electric current. Electroless nickel-phosphorus coating consists of an alloy of nickel and phosphorus. The process relies on the presence of a reducing agent, for example hydrated sodium hypophosphite (NaPO₂H₂·H₂O) which reacts with the metal ions to deposit metal. The alloys with different percentage of phosphorus, ranging from 2-5 (low phosphorus) to up to 11-16 (high phosphorus) are possible. The metallurgical properties of alloys depend on the percentage of phosphorus.

EN has several advantages versus electroplating. Free from flux-density and power supply issues, it provides an even deposit regardless of workpiece geometry, and with the proper pre-plate catalyst, can deposit on non-conductive surfaces.

Advantages include:

1. Does not use electrical power.
2. Even coating on parts surface can be achieved.
3. The process can plate recesses and blind holes with stable thickness.
4. High wear resistance and excellent corrosion resistance
5. Easily soldered with a highly active acid flux
6. Matte, Semi Bright or Bright finishes can be obtained.

Disadvantages include:
1. Lifespan of chemicals is limited.
2. Waste treatment cost is high due to the speedy chemical renewal.

Each type of electroless nickel also has particular advantages depending on the application and type of nickel alloy

Applications

It is commonly used in engineering coating applications where wear resistance, hardness and corrosion protection are required. Applications include oil field valves, rotors, drive shafts, paper handling equipment, fuel rails, and optical surfaces for diamond turning, electrical/mechanical tools and office equipment. It is also commonly used as a coating in electronics PCB manufacturing, typically with an overlay of gold to prevent corrosion. Coatings of 25 to 100 micrometres can be applied and machined back to final dimensions. Its uniform deposition profile mean it can be applied to complex components not readily suited to other hard wearing coatings like hard chromium.

Its use in the automotive industry for wear resistance has increased significantly, however it is important to recognize that only End of Life Vehicles Directive or RoHS compliant process types (free from heavy metal stabilizers) may be used for these applications.

Bath composition and operating conditions

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel</td>
<td>5.5-6.5g/l</td>
</tr>
<tr>
<td>Sodium Hypophosphite</td>
<td>25-35/l</td>
</tr>
<tr>
<td>pH</td>
<td>4.2-5.2</td>
</tr>
<tr>
<td>Temperature</td>
<td>85-95°C</td>
</tr>
<tr>
<td>Agitation</td>
<td>mild air</td>
</tr>
<tr>
<td>Deposition rate</td>
<td>15-25 micron meters/hr</td>
</tr>
</tbody>
</table>
References


7. PRINTED CIRCUIT BOARD MATERIALS HANDBOOK. Martin W. Jawitz.
