PlasmaPREPLATE: An Environmentally-Friendly Surface & Heat Treatment for Wire, Tube and Strip Plating

Plasma has been used in the industry for a range of surface treatment applications for a few decades. In the last decade plasma was introduced in the production of endless metal materials such as wire, tube and strip. In the first half of this paper a general overview of Plasmait’s heat and surface treatment for wire/tube/strip is outlined.

In the second part, this paper sets out application of plasma technology in plating processes on non-ferrous materials i.e. copper and copper alloys. In this document two processes are considered in more detail:

1. Hot dip tin plating of copper and copper alloy wire, tube and strip
2. Electroplating of copper and copper alloy wire, tube and strip.

Plasma can simplify plating processes by replacing chemical treatments, which make then friendlier to the environment and the operator. In plating plasma process is used to:

(A) Anneal or preheat the material to a required temperature prior to plating and;
(B) Clean and activate the surface to facilitate effective plating (inter-metallic bonding)

Plasma treatment replaces pickling and fluxing in the hot dip Tinning process. Plasma treatment can also be adjusted to allow simultaneous annealing, should this be required to achieve required mechanical properties of the finished product. This makes plasma process much cleaner and economical than the traditional cleaning processes.

In the electroplating process plasma can replace acid degreasing and rinsing. The surface cleanliness of plasma treated wire can be electroplated directly with Ni, Sn, or Ag without the need for chemical treatment. Plasma process is used to its full advantage when it is set to perform simultaneous annealing to ensure required softness of the material. The ability to target required softness allows simplification of upstream wire drawing process. Final drawing becomes unnecessary when bell annealing is used. This is due to the fact that plasma heat treatment achieves required mechanical properties with sufficient tolerance to meet the specification of the finished product.

Plasma heat and surface treatment runs inline with both, the hot dip or electroplating process. Plasma annealing is most suitable for applications that require good surface quality. Plasma process is therefore particularly suited for applications that cannot tolerate surface defaults commonly caused by resistive annealing.
General Overview of Plasmait Treatment

Plasma takes many different forms. In our particular case plasma is generated by electrically charging a small amount of gas inside the plasma chamber.

In plasma, gas particles (atoms and molecules) constantly collide and exchange energy by switching to higher and lower energy states. When colliding, some particles begin to emit light; others become ionised - divided into free (positive) ions and free (negative) electrons.

Electrically charged particles make plasma different from other states of matter. Charged particles can be accelerated in the electric field to a desired speed and directed to a target.

In Plasma Chamber the electric field accelerates ions towards the wire/tube surface (positive electrode) and electrons towards the edge of the heating chamber (negative electrode - earth). Shown in Figure 1, the electric field in the heating chamber accelerates charged particles between the outer wall of the heating chamber and the wire/tube. On their way to the opposite electrode, the particles collide with other atoms and molecules. The less they collide (or the less interrupted their journey) the faster they accelerate and the larger their impact on the wire/tube surface. To achieve high impact heat treatment one has to apply a vacuum to the heating chamber.

**Figure 1:** Schematic of Plasma treatment process inside the heating chamber
A Plasma Chamber, ensuring sufficient power/heat for the process, is filled with low-pressure inert gas to prevent a chemical reaction between the gas and the wire/tube which is fed through the sealing system and the heating chamber, continuously thereby exposing the wire/tube surface to ion bombardment.

The effect of such bombardment is threefold: (1) efficient heating, (2) surface smoothing and (3) surface cleaning such as degreasing and deoxidation. The degree and type of surface treatment can be manipulated with the choice of process gas.

Plasma process can improve economics of the production process for many wire, strip and tube production applications. This is a result of process simplification through a replacement of batch annealing and introduction of an in-line process. Plasma treatment can be used as an alternative to chemical cleaning. Plasma treatment achieves high degree of surface cleanliness and outstanding product quality through accurate physical properties of the material in the end product.

The outstanding cleaning and smoothing capabilities of plasma technology benefit applications in the fields such as medical, aviation, aerospace and other precision wire/tube manufacturing as well as galvanising, extrusion, enamelling, and winding/magnet wire manufacturing.

**General Line Composition of a Plasmait System**

A Plasma Annealer consists of three main components:

1. Vacuum and Sealing System
2. Power Supply/Heating Module
3. Cooling System with Gas Supply

**The Sealing System** (Figure 3) is deployed to maintain low-pressure inert gas atmosphere in the heating chamber. It prevents air from entering the heating chamber and hence reduces consumption of process gas. The Vacuum Systems collects the dirt from the wire/tube surface, which is deposited in the air filters.
Two sealing modules are installed on each side of the Heating Section. The Sealing System makes the use of a contact-less technique and allows a range of wire diameters to be processed through the same sealing module. The small sealing module can be utilized on wire diameters of between 0.1mm and 2mm (0.004” – 0.0785”) and the large module on diameters of between 1.5mm and 3mm (0.06” – 0.12”). This simplifies the process handling and shortens the downtime during the batch changeover. It takes a few simple steps and a maximum of 5 minutes to upload new material and start the process. Stringing in a wire with a different dimension should take no more than 2 minutes. Tube diameters suitable for plasma processing are larger than the above mentioned wire diameters, subject to mass throughout/wall thickness involved.

**The Heating Module** (Figure 4) is the heart of the device in which the plasma generation takes place and where the input power is computer controlled. The chamber, depending on the execution and actual power, has a length of 0.5m – 1m (approx. 1.5 – 3.3’). The standard plasma chamber has a power input of 8kW.

The wire/tube is led through the Heating Module where it is exposed to high-density plasma. The intensity of plasma treatment is regulated by the Power Supply unit, the integral part of the Heating Module.

**The Cooling Section** (Figure 5) is an additional element of the Plasma Annealer. It is used to prevent oxidation of the/tube surface at the point when the wire/tube exits the machine. The Cooling Section can entail water cooling, gas cooling or a combined system, depending on the type of material or surface quality requirements of the finished wire/tube.

![Figure 3: Sealing System module at the inlet point of Plasma Annealer.](image)

![Figure 4: 8kW Heating Module in a Plasmait Plasma Annealer.](image)
Operational Benefits of Plasma Process

Plasma annealing process offers considerably higher output compared to traditional strand annealing. This is due to concentration of energy in plasma i.e. flame energy density in the plasma chamber. One plasma heat treatment line can replace 5 - 20 lines on a strand annealer. This makes it possible to run Plasma Annealer inline with drawing on a number of applications. A replacement of a tube annealer with plasma technology would allow for radical reduction in the number of processing lines, including the pay-off and take-up facilities. By the same token, the potential reduction in working capital can be of great benefit to the manufacturers of expensive wires/tubes.

The output of Plasma Annealer is still lagging behind the outputs achieved by traditional resistive annealers for diameters larger than 1mm. However, the surface quality of the end product achieved with plasma technology is considerably higher, which is a consequence of the surface cleaning and polishing effect during the plasma treatment. This makes plasma technology particularly suitable for applications that require uncompromising surface quality such as enamelled and plated wire/tube.

Plasma treatment is easy to operate and does not involve any hazardous chemicals nor does it release unnecessary heat into the operator’s environment. The process is computer automated allowing for integration into the controls of the complete production line. Plasma process is started and stopped immediately without heat-up and cool-down period. Products of different diameters and materials can be strung-in and changed over in a matter of minutes.

Plasma offers low processing and maintenance costs. Energy conversion rate [electrical power vs. heat released to the material] is between 50% and 80%, subject to application.
Plasma technology benefits from low-cost processing and maintenance. The cost of operation of Plasma Annealer was quantified in the four trials on copper, stainless steel and bronze wire provided in Table below.

<table>
<thead>
<tr>
<th>Material</th>
<th>Copper</th>
<th>Copper</th>
<th>Stainless Steel</th>
<th>Bronze</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>mm</td>
<td>1.6 mm</td>
<td>1.6 mm</td>
<td>2 mm</td>
</tr>
<tr>
<td>Inlet Temperature</td>
<td>°C</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Annealing Temperature</td>
<td>°C</td>
<td>550</td>
<td>230</td>
<td>600</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>N/mm²</td>
<td>220 - 230</td>
<td>260</td>
<td>360</td>
</tr>
<tr>
<td>Wire Speed</td>
<td>[m/s]</td>
<td>3</td>
<td>7.5</td>
<td>1</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>kW/h/Kg</td>
<td>0.08</td>
<td>0.35</td>
<td>0.28</td>
</tr>
<tr>
<td>Gas Consumption</td>
<td>N/l/Kg</td>
<td>0.9</td>
<td>0.5</td>
<td>1 - 2</td>
</tr>
<tr>
<td>Maintenance Expenditure</td>
<td>€/Kg</td>
<td>0.008</td>
<td>0.005</td>
<td>0.02</td>
</tr>
</tbody>
</table>

*1* Single Heating Module and 95% Up-Time

*2* Litre of gas at Normal Conditions per kilogram of wire material

*3* Per Kilogram of wire material

*4* Values depend on material quality and treatment history

*5* Depends on the material

*6* Depends on processing gas

Plasma process has all the benefits of contact-free processing, which contributes to a low cost of maintenance. Maintenance is limited to changing of oil and air filters and replacement of electrical contacts. The Plasma Chamber may have to be wiped with a dry cloth as required, depending on the amount of dust deposit on the inlet wire/tube. In the case of a high degree of dirt on the wire surface pre-cleaning is required.

**Product Quality through Plasma Treatment**

Plasma treatment offers homogenous mechanical properties such as yield strength, tensile strength and grain size. The consistency and low deviation from the required mechanical properties can benefit many applications, in particular copper alloys and special metal processing.

Plasma heat treatment can be used for full re-crystallisation annealing reaching the softness usually obtained only in bell annealers. For example the elongation of plasma annealed 2mm copper wire reached 46% - 48%. Tensile Strength and Yield Strength of same copper wire measured 220 - 230 N/mm² and 50 – 60 N/mm² correspondingly.
For fully annealed copper wire the Tensile Strength does not vary more that ± 2 N/mm². The tolerances are larger for medium annealed wire that is in the “steep curve range”, where elongation changes quickly with temperature. For example, specific mechanical properties can be targeted accurately with Plasma annealer also in the “semi soft” range. Plasma annealing on 1.5mm copper alloy resulted in the following tolerances:

- **Yield Strength**: 405 N/mm² ± 12 N/mm²
- **Tensile Strength**: 510 N/mm² ± 20 N/mm²
- **Elongation**: 4% ± 1%

In comparison, 2mm copper tube was annealed to the softness of 60% elongation.

The process control system allows for highly accurate control of wire/tube softness during the production process. The annealing temperature can be changed during the process making it possible for wire/tube softness to be manipulated on-line to the desired grade during the process.

One of the main advantages of plasma treatment is the surface quality of the processed material. Plasma treatment is a dry alternative to acid/alkaline cleaning. Plasma does not leave acid residues on the wire/tube surface and hence prevents subsequent surface oxidation on the wire/tube surface. Plasma can deoxidise the surface of non-ferrous materials.

The applications where plasma treatment demonstrated the most benefits are:

- Plasma annealing/pre-heating and surface cleaning in-front of extrusion, enamelling, cladding for improved adhesion of the coating;
- Plasma annealing and acid-free cleaning inline, in front of electroplating;
- Plasma annealing and cleaning in front of hot dip plating.
APPLICATION: Plasma Treatment for Hot Dip Tinning of Copper

Tinning or tin plating of copper is used predominately to provide corrosion protection of copper surface. Traditionally, tin plating of copper wire is performed by running the wire through a tin bath and drying it vertically in order to allow the tin coat to dry on the copper surface. The inter-metallic bond can be achieved only if the copper surface is clean and appropriately activated. Acid cleaning or pickling has traditionally been used to pre-clean the wire surface. Surface activation is commonly obtained with fluxing, which is a dirty and environmentally compromising process. The Diagram below compares the traditional process of hot dip tin plating to new PlasmaPREPLATE process developed by Plasmait GmbH.

PlasmaPREPLATE process pre-heats (anneals) and cleans the wire before it enters the tin bath to allow tin adhesion on the copper surface.

**TYPICAL PRODUCTION PARAMETERS of PlasmaPREPLATE PROCESS:**

- **Material:** 2mm copper wire
- **Process speed:** 90m/min
- **Output:** 150 kg per hour
- **Power input:** 10 kW
- **Total Power Consumption:** 0.06 kWh per kg of produced wire
- **Process Gas Consumption:** 1.37 NI of Nitrogen per 1kg of produced wire
- **Maintenance Expenditure:** € Cent 0.6 per kg of produced wire @ 95% up-time

PlasmaPREPLATE process can be adjusted to perform simultaneous annealing of the wire to a required softness. The wire enters the tin bath at temperature, which in turn heats the bath reducing the need for additional heating on the bath, and hence saving the energy used.
in the process. PlasmaPREPLATE process ensures complete degreasing and deoxidation whilst activating the surface to meet the conditions for strong inter-metallic bond. Superior surface cleanliness and activation allows the temperature of the tin bath to be reduced to 260°C compared to 300°C or higher commonly used in the traditional process. Low temperature of the bath limits solvency of copper in the bath, which in turn reduces the need for cleaning of the tin bath, saving on the cost of tin. More importantly, low temperature of the bath allows the manufacturer to produce a wider range of hard finished products, which is not possible in the traditional process. Hard copper wire would inevitably soften in a bath with a temperature over 300°C.

Traditionally, lead is added to a tin bath to improve adhesion of the coat. PlasmaPREPLATE process improves the adhesion of the coat to a degree that lead can be omitted in the bath. This is becoming increasingly important in the electronics industry due to the new regulation concerning the lead content in the consumer electronics components.

Figure 6: PlasmaPREPLATE machine designed for hot dip tin plating of copper wire.

PlasmaPREPLATE process can be used for production of wire, strip and tube such as capillary tube used in fridges, air-conditioning systems as well as for various tinned conductors that require good corrosion protection.
APPLICATION: Plasma Treatment for Electroplating of Copper

Electroplating was introduced a few decades ago as an alternative to hot dip process. Electroplating offers faster, single-line production as well as better control over coat thickness i.e. usage of the plating material. Electroplating process can run at the speeds of up to 15m/s. This is too slow for the process to be integrated inline with the upstream drawing lines that operate resistive annealers. As represented in Diagram below, electroplating line runs usually independently of a drawing line with a resistive annealer. The applications such as copper alloys and those that cannot tolerate surface defects created by resistive annealing usually employ bell annealing technique. The two alternative processes are depicted in the Diagram below.

As an alternative to the traditional processes PlasmaPREPLATE can be deployed inline with an electroplating line, replacing the need for pickling and rinsing whilst annealing the wire/tube to a required softness prior to plating. This configuration improves the environmental footprint of the process and releases the upstream annealing capacity. Furthermore, drawing operation can be placed in front of PlasmaPREPLATE machine to ensure single line operation with the electroplating machine. This requires an adoption of a
slower, but considerably less expensive drawing machine that runs at the speed up to 15m/s, the limit set by the electroplating line.

In the case of copper alloys, final drawing can be abolished by targeting specific softness parameters with the use of PlasmaPREPLATE machine or PlasmaANNEALER. In this way a four stage process of (1) drawing, (2) bell annealing, (3) final drawing, and (4) electroplating can be reduced to a single line as depicted in the diagram above. This would mean that running PlasmaPREPLATE machine in a plating line could avoid two sets of takeups and payoffs, final drawing, pickling, rinsing as well as release the capacity in the upstream drawing line and bell annealer. Horizontal PlasmaPREPLATE machine for electroplating applications is given in Figure 7.

![Figure 7: A picture of the horizontal PlasmaPREPLATE machine designed for annealing / preheating and cleaning of copper wire/tube for electroplating.](image)

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