Plasmait GmbH
Philipsstraße 27/C3, 8403 Lebring, Austria
Tel +43(0)3182-52-475
Fax+43(0)3182-52-475-4
www.plasmait.com
info@plasmait.com
FBNr.: FN 00238404w
UID-Nr.: ATU 57271419

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Technical Paper:

PLASMA ANNEALING OF THIN-WALL AND SMALL DIAMETER TUBES:

Efficient, High-Speed Alternative to Traditional Radiance Annealing.

Authors:
Igor Rogelj, Commercial Director, Plasmait GmbH
Peter Ziger, R&D Director, Plasmait GmbH
Primoz Eiselt, MD, Plasmait GmbH
Andy Houghton, Promet Consulting Ltd

ABSTRACT

The paper outlines plasma annealing of thin-wall and small diameter tubing. The principles of plasma heat and surface treatment are explained as ion bombardment on material surface. The workings and functionality of the plasma annealer and its components are outlined.

Plasma annealing is compared to the traditional tube/strand type annealing in terms of:
- Process layout;
- Production speed/output;
- Power and gas consumption;
- Maintenance;
- Mechanical and surface properties;
- Quality control with inline defect detection.

The focus is given to small diameter and thin wall tubing with demanding surface and mechanical requirements in the medical, aerospace, automotive and instrumentation tubing sectors.

The article concludes that plasma annealing offers a cost effective alternative to traditional tube/strand annealing in the small diameter and thin wall tubing of many ferrous and non-ferrous materials. Plasma annealing advantages in process efficiency and finished product quality more than outweigh marginally larger capital investment in the annealing plant for many applications.

INTRODUCTION TO PLASMA TREATMENT

Plasma is ionised gas. Electrically charged particles make plasma different from a normal gaseous state of matter. Charged particles can be accelerated in the electric field and directed to a target.

Shown in the schematic in Figure 1, Plasma is maintained in the plasma chamber at low pressure. In the plasma chamber the electric field accelerates ions towards the surface of the processed material and electrons towards the outer wall of the chamber. Ion bombardment results in heating on the surface of the processed material. On the other hand the electrons have virtually no mass and carry no energy, therefore do not heat the plasma chamber as they hit its inner wall. It is only the radiation from the glowing material surface that conveys heat to the plasma chamber. This makes plasma annealing an efficient technique to heat the material, resulting in only a very small percentage of power lost as heat dissipated into the environment.

The plasma chamber is filled with low-pressure inert gas to prevent chemical reaction between the gas and the processed material. The processed material is fed through the sealing system to the heating chamber, continuously thereby exposing the wire surface to ion bombardment.

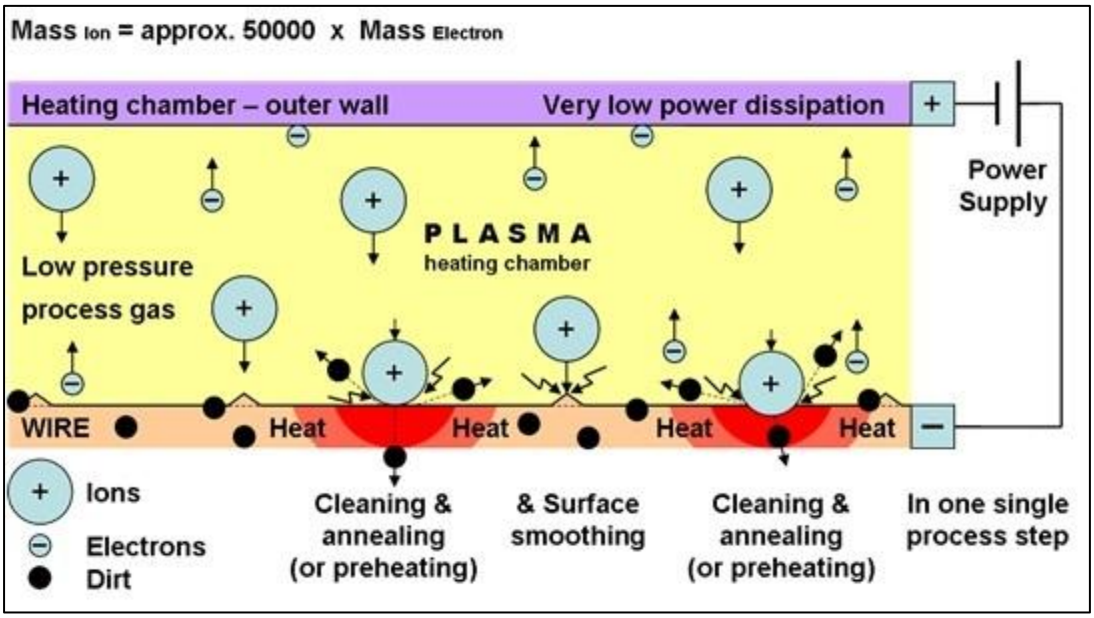

Figure 1: Schematic of plasma treatment in the Plasma Chamber

The effect of ion bombardment on the material surface is threefold:

1. efficient heating;
2. micro surface smoothing (increased micro roughness) and
3. surface cleaning i.e. degreasing and surface oxide removal.

The degree surface treatment depends on material being processed and the choice of purging gas.

PLASMA ANNEALER AND ITS COMPONENTS

Plasma heat and surface treatment has so far found its place in many continuous annealing and cleaning applications in the wire and tube production. Over 60 plasma continuous annealers have been installed in the industrial applications to date. The deployments benefited many ferrous and non-ferrous applications for production of round and flat wire as well as tube.

An example of a plasma annealer designed for continuous high-speed annealing and surface treatment of stainless steel tubes with diameters of up to 3mm OD is given in Figure 2. In Figure 3 is a photo of a plasma annealer integrated in a vertical hot dip tinning line for flat copper wire of widths up to 8mm or tube with diameters up to 3mm OD.

Figure 2: Plasma annealer for stainless steel tube with inbuilt transport system

Figure 3: Plasma annealer as part of copper wire or tube tinning line

A typical plasma annealer consists of five components:

1. Plant frame;
2. Sealing system with vacuum pumps;
3. Heating module with power supply;
4. Cooling section with gas supply;
5. Controls;

Plant frame is made of a steel structure usually in a horizontal configuration (Figure 2). A guiding rail is fitted on the steel frame to allow for horizontal adjustment of heating module, sealing system and dwell module. This simplifies string-in procedure, which can be done in a few minutes.

The sealing system (Figure 4) in combination with vacuum pumps maintains low-pressure inert gas atmosphere in the heating chamber by preventing air from entering the heating chamber. The sealing system does not touch the processed material. This prevents from excessive wear of the sealing dies and avoids compromising material surface. The vacuum system sucks out the gas that has been contaminated with the surface deposits removed from the processed material, which are filtered out through the exhaust installation.

The processed material is led via the sealing system through the heating module (Figure 5) where it is exposed to plasma treatment. Multiple heating modules with power supplies can be installed in the annealer to meet the heating requirements of specific applications. An appropriate length dwell module is located immediately after the heating module to allow appropriate dwell time for specific application.

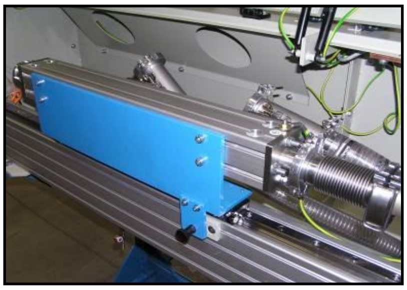

Figure 4: Sealing System

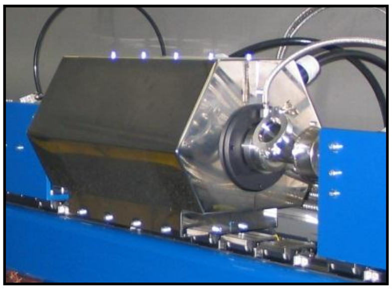

Figure 5: Heating Module

Figure 6: PLC Controls

Gas cooling section is located after the dwell module. Plasma annealer can be equipped with water cooling combined with the gas cooling system if necessary for the application.

Plasma annealers can include an inbuilt transport system to ensure appropriate speed and tension control of the material in production (see capstans in Figure 7). The annealer can then be integrated with the appropriate takeup and payoff or installed in-line with a drawing machine, rolling mill or subsequent coating process.

Plasma annealer is equipped with PLC controls and touch screen HMI (Figure 6) to allow for computer assisted adjustments to production parameters and its storage in the recipe database. Individual components of the annealer are visualised for user-friendly operation.

Plasma annealer for production of tubes can be equipped with an in-line defect detection system, which records the location and size of any puncture in a tube wall.

Figure 7: PlasmaANNEALER for SS Tube

Plasma Annealer vs. Traditional Tube/Strand Furnace

Slow annealing speeds in the traditional tube or strand furnace mean that the annealing of stainless steel or nickel alloys tubes has to be performed in multi-line configurations. Multiline production requires considerable capital investments in transport systems, payoffs and takeups. Multiline configuration takes extra floor space and requires more manpower for material manipulation. The material processed on a multiline furnace also locks-in a significant amount of working capital.

The production speed of plasma annealer can be up to 10 times the speed of the traditional tube furnace. This allows for a considerable reduction in the number of lines for the same annealing output. In some cases plasma annealing can run in-line with a drawing machine, rolling mill or subsequent coating process, which can further simplify production and reduce material manipulation.

COMPARISON OF PRODUCTION COSTS

Plasma offers considerable energy savings compared to the traditional tube furnace. Ion bombardment on the material results in heating being directed to the material, with only minor radiation loses in the heating module. The energy efficiency – which is measured as heat induced in the material vs. total power of plasma annealer during normal production – is for plasma annealer between 70% - 85%, subject to application. The energy efficiency of a traditional tube furnace is about half that value. Energy efficiency of a traditional tube annealer drops further in case of underutilisation and when energy used during lengthy heating up is considered.

Energy used for running multiple takeups and payoffs in a multiline tube furnace also add to the total cost of energy required to run the annealing plant. This should be taken into account when energy balance is compared for the two alternative annealing processes.

Furthermore, plasma annealer requires up to 80% smaller power connection, which can on its own be a substantial cost saving.

Replacing a traditional tube furnace with a plasma annealer brings substantial energy related saving. Energy savings will depend on specific application, production patterns, the type of furnace (electrical or gas fired furnace) and of the price of energy to the producer. The actual energy savings are therefore specific to individual producer and cannot be quantified in general.

The type of purging gas used in plasma annealing depends on application and surface requirements of the finished product. Nitrogen is commonly used in non-ferrous applications. Hydrogen, argon, helium or their mixture can be used on stainless steel applications that require good surface finish. Forming gas can also be used in ferrous applications.

Plasma annealing consumes noticeably less purging gas than the traditional tube furnace. This is due to fewer lines in operation and the fact that purging gas is fed to the plasma zone at low pressure. The gas cooling utilizes a closed-loop system to further reduce the gas consumption. Purging gas savings are particularly substantial when expensive purging gas such as hydrogen is used.

Hot material in the plasma/heating zone does not touch any parts of the machine due to the short length of the plasma/heating section. This considerably reduces the maintenance costs related to tube wear that are common for a tube furnace and prevents contamination of the processed material surface. The maintenance of plasma annealer involves regular changing of vacuum pump filters and oil in the vacuum pumps. Electrode and protective glass tube in the heating module have to be cleaned regularly.

Unlike the traditional tube furnace, the plasma annealer can cold start production in few minutes and can be stopped imminently. This avoids the lengthy heating-up and cooling-down times and associated energy costs that are symptomatic for a conventional furnace.

COMPARISON OF FINISHED PRODUCT QUALITY

High speed annealing does not only bring operational savings. Rapid heating and reduced time of recrystallization bring the benefits of small grain size. The photo in Figure 8 depicts a glowing 0.5mm stainless steel wire at the exit of plasma chamber. The wire was annealed at the speed of 6m/s. The microscopic photo in Figure 9 indicates homogenous annealing across the cross-section of the wire and grain size below 10 micron. High speed plasma annealing features small grain size and delivers homogenous crystal structure in the longitudinal and transversal direction, which in turn improves material’s susceptibility to cold working. For example, plasma annealed materials that have been recrystallized and feature homogenously small grain size in all directions and superior surface finish demonstrate better cold working properties and lower drawing die wear rate. Annealed materials with small grain size will also better resist surface cracking during bending process. Homogenous grain size is also a benefit to producers of tubes for heating elements, where small radius bending is applied to the material.

Plasma annealer allows the operator to manipulate annealing temperature via power input on a power supply instantaneously and with a high degree of accuracy. This gives the operator the ability to target mechanical properties with a great degree of accuracy, which can speed up new product development.

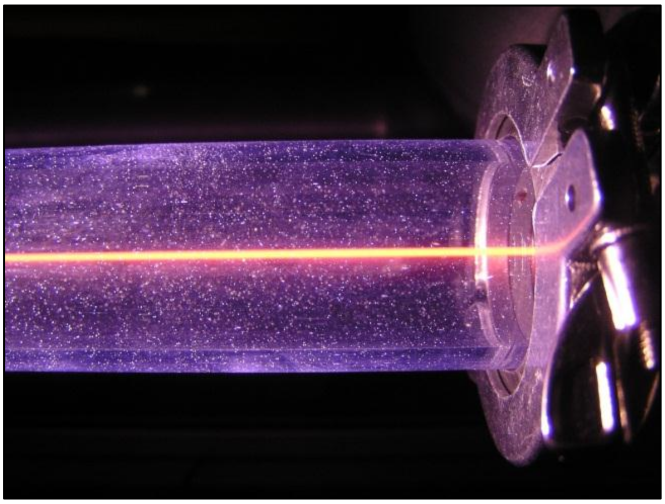

Figure 8: Glowing SS wire with diameter of 0.5mm plasma annealed and cleaned at 6m/s.

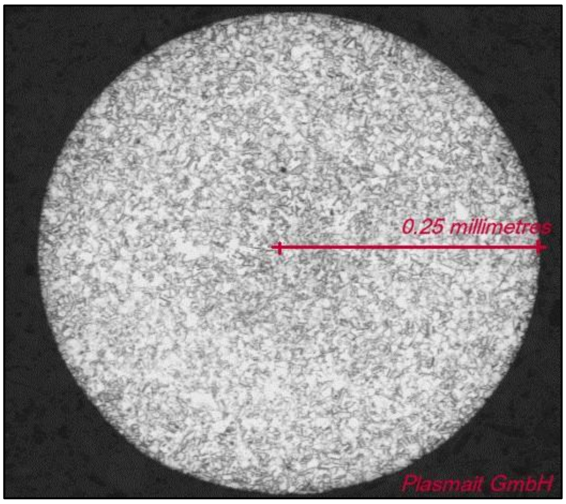

Figure 9: Cross-section of 0.5mm SS wire annealed in plasma at the speed of 6m/s.

Plasma treatment facilitates simultaneous heat and surface treatment on the processed material. Dirty deposits, soaps, lubricants and oxides layers break up and disintegrate at high temperature under the ion bombardment in the plasma chamber and are then filtered out through the exhaust pipe.

Plasma treatment is not designed for removal of excessive amounts of dirt and soaps on the material surface, which has to be removed prior to plasma treatment with an appropriate pre-cleaning system. Plasma surface treatment is only effective on a surface with minor contamination and should be regarded as a fine surface cleaning, effective only for removal of thin layers of surface deposits.

The effect of ion bombardment on the surface of the processed material manifests itself in a clean and degreased surface. Removal of thin oxide layer is also achieved in many stainless steel, copper and copper alloy applications with appropriate production settings.

Plasma treated surface without the oxide layer is highly susceptible to coating and would create a strong bond with polymers or metals. To maximise the adhesion in subsequent coating, plasma annealer has run in-line with the coating process, whereby non-oxidising atmosphere has to be ensured to the point of coating.

Materials that have undergone plasma treatment must be cooled down in protective atmosphere in order to prevent surface oxidation. On the exit of the material from the cooling section (i.e. at temperatures close to room temperatures) stainless steels, copper and copper alloys create a thin invisible layer of oxide, which passivates the surface and protects the material from further oxidation.

Plasma surface treatment leaves the surface clean, dry and without catalysts for further oxidation, common for chemically treatment processes. The fine oxide layer on the dry, chemically-free plasma cleaned surface is therefore less prone to deterioration than the oxide layer on the chemically cleaned surface.

The table below summarises a qualitative comparison of plasma annealer with a traditional tube furnace for small diameter and thin wall tubing in terms of required investment, cost of operation and finished product quality.

	Traditional Tube Annealer	Plasma Annealer
Process type	**Multi-line / low-speed**	**Single line / high-speed**
Energy cost	**High**	**Low**
Purging gas cost	**High**	**Low**
Labour cost	**High**	**Low**
Maintenance cost	**High**	**Low**
Production uptime	**Low -** Long cooling down and heating up	**High -** Immediate start and stop
Commissioning time	**Long**	**Short**
Production line footprint	**Large**	**Compact**
Annealing power/temp. control	**Limited / Slow**	**Accurate and immediate**
Capex – furnace	**Low**	**High**
Capex – payoffs and takeups	**High**	**Low**
Working capital locked in material	**High**	**Low**
Grain size of finished product	**Large**	**Small**
Inline defect & surface quality detection	**Non**	**Included**

CONCLUSION

The evaluation of the effectiveness and efficiency of plasma annealing for production of small diameter tubes (OD below 6mm) has shown favourable results. The benefits of plasma annealer in comparison to the traditional tube or strand furnace are evident in many operational aspects as well as in the quality of the finished product. The savings offered by plasma annealing in terms of gas and power consumption, manpower and maintenance alone should make many producers of small diameter tube consider plasma seriously. Good quality of the finished product and flexibility in new product development alone may be sufficiently good reason for a specialist tube producer to invest in plasma annealing.

The capital investment in a plasma annealing plant is likely to be higher than the capital investment required for a traditional tube furnace. Nevertheless, the difference in the total investment for each alternative becomes comparable when the investment in all periphery equipment including multiple transport systems, takeups and payoffs as well as costs of floor space, power connection and commissioning are included in the total.

Extra capital investment in plasma annealing can be quickly repaid once on-going production savings are taken into account. Some of our calculations show that the repayment periods for small diameter and thin wall copper, copper alloy, stainless steel and nickel alloy tubing could be less than one year.

Igor Rogelj, Commercial Director
Peter Ziger, R&D Director
Primoz Eiselt, Managing Director
Plasmait GmbH
UK/International: +44 7810810656
Austria: +43 318 252 4755
info@plasmait.com, www.plasmait.com