SCRATCH-FREE & PILE-FREE PLASMA ANNEALING OF STAINLESS STEEL AND NICKEL ALLOY WIRE, ROPE &TUBE
A fast, efficient and cost effective alternative to bright strand annealing process.

The strand annealing furnace has for decades played the dominant role in annealing of wires, ropes and tubes made of stainless steel and nickel alloys. It has been difficult to imagine an alternative to the king of continuous annealing in applications such stainless steel and nickel alloy wire and rod. Yet, with increasing cost of energy, purging gases, labour, and ever more demanding environmental and quality standards it is time to consider plasma annealing in a new light.

PlasmaANNEALER has already found its place in many high-end applications such a high quality medical wires, ropes and strands, medical and aerospace tubes, as well as electronics and jewelry applications, where clean, scratch-free and pile-free surface is required. With a new, third-generation design Plasmait brought to the market a set of small-footprint, high-output PlasmaANNEALERs that are aimed at mainstream stainless steel and nickel alloy applications that challenge the dominance of the traditional strand annealing furnace in pretty much every aspect. The new PlasmaANNEALER surpasses the traditional furnace in operational efficiency and finished product quality, whilst offering lower total cost of ownership.

The slow speed of traditional tube furnace means that the annealing of stainless steel and nickel alloy wires generally involves a multi-line set up. Multi-line process is logistically demanding and involves multiple pay-offs and take-ups that can require substantial capital outlay. A multi-line annealing plant takes large workshop area and locks considerable money in working capital related to the material being processed on each of the annealing lines. Furthermore, slow annealing speed means that the drawing or rolling processes have to be performed separately, off-line from annealing, which adds to the complexity of process logistics.

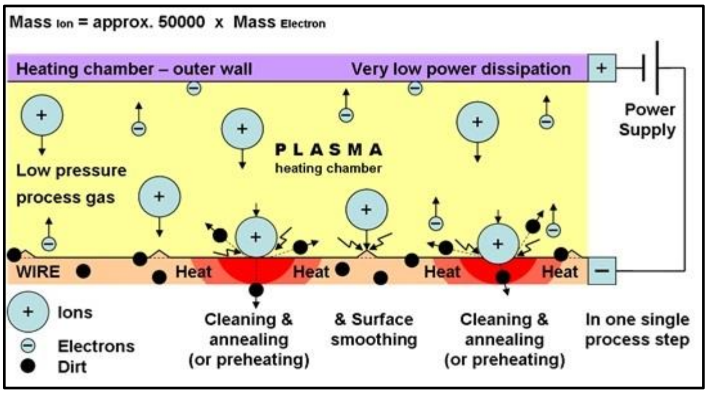

Figure 1. Schematic of plasma treatment

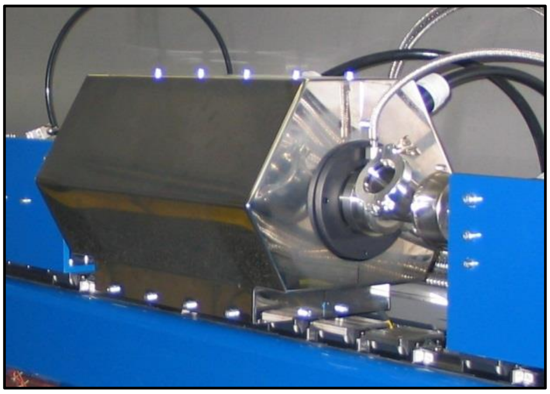

Figure 2. Plasma module

The process speeds of the new plasma annealer are much higher than the process speeds of a traditional tube furnace. This allows a single line plasma annealing plant to substitute multiple lines of a tube annealer, whilst retaining the same output capacity. In some cases it is also possible for plasma annealer to operate in-line with a drawing or a rolling machine.

In **Figure 1** is given a schematic of a plasma treatment on a metal surface in the plasma chamber. Plasma – an ionized gas - is maintained in the plasma chamber (**Figure 2**) 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 they do not heat the plasma chamber. This makes plasma annealing an efficient technique to heat the material, resulting in only a very small percentage of power being lost as dissipated heat in the plasma chamber. The energy coupling in the plasma process is considerably better than the energy coupling in the typical convection furnace, which is the reason for a compact design of the plasma chamber. Depending on application 70% to 85% of all the power used by plasma annealer is converted into heat in the processed material, which makes the plasma heating much more energy efficient than any conventional tube furnace – a feature that has been gaining importance and is unlikely to change in years to come.

Typical plasma annealers for stainless steel and nickel alloy materials are designed for materials with cross-sections of up to about 300mm^2 (0.46 in^2). Plasma annealing allows for a radical increase of continuous annealing speeds of stainless steels and nickel alloys. The annealing speeds on fine and ultra-fine wires of austenitic stainless steels can reach up to 25m/s (5000ft/min). For small diameters wire (below 0.6mm or 0.024′′) plasma offers annealing speeds that are high enough to run annealing in-line with standard drawing machine or a cold rolling mill. This has so far not been possible with any traditional annealing technique. Yet on the larger diameters (i.e. up to 5.5mm or 0.22′′) the cooling represents the limiting factor for annealing speeds. The main reason for increased annealing speeds is plasma’s superior energy coupling compared to the energy transfer achievable in the traditional convection or radiance furnace. Typically, the output of a single line plasma annealer can reach up to 170kg per hour for recrystallization of austenitic stainless steel wire and more for martensitic stainless steels and copper alloys. The annealing speeds can be increased by adding additional plasma power as long as appropriate cooling arrangement is ensured to meet the requirements of a specific material and annealing application.

Rapid heating and reduced time of recrystallization results in fine grain size. The microscopic photo of the cross-section in **Figure 3** indicates uniform crystal structure which was observed on a 0.5mm (0.02′′) austenitic stainless steel wire that was plasma annealed at the speed of 6m/s. Small grain size with uniform crystal structure in the longitudinal and transversal direction improves material’s susceptibility to cold working and its resistance to surface cracking.

Annealing power is controlled instantaneously and with a high degree of accuracy via a high power supply. This gives the operator the ability to target mechanical properties with a great degree of accuracy and provides greater flexibility in new product development.

Ion bombardment or ion sputtering on the material surface results in removal of the upper surface layer which makes up for an effective surface treatment. Dirty deposits, soaps, lubricants and fine oxides layer break under the ion bombardment in the plasma chamber. The debris and other cracked surface contamination are sucked out of the plasma chamber by the vacuum system and are filtered out through the exhaust installation. The dry surface cleaning and degreasing being performed simultaneously with plasma annealing is of particularly benefit to applications with demanding surface requirements in sectors such as medical, welding or aerospace to mention a few.

Plasma treatment is nevertheless not designed for removal of excessive amounts of dirt and soaps on the material surface. Excessive surface contamination has to be removed with an appropriate conventional pre-cleaning system that is chosen for specific application.

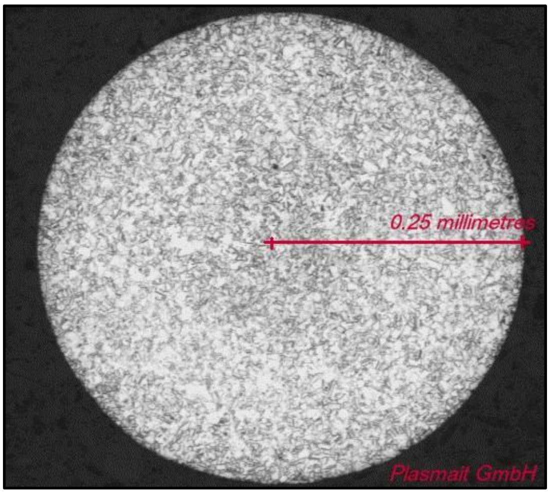

Figure 3. Cross-section of 0.5mm SS wire annealed in plasma at the speed of 6m/s.

Figure 4. PLC controls with Siemens HMI

Plasma treated surface without the oxide layer is activated and highly susceptible to coating and creates a strong bond with polymers or metals. The plasma annealer can be installed in-line with the coating process, such as electroplating, hot dip, taping or extrusion coating, whereby non-oxidizing atmosphere is ensured to the point of coating to avoid the need for wet surface preparation or fluxing.

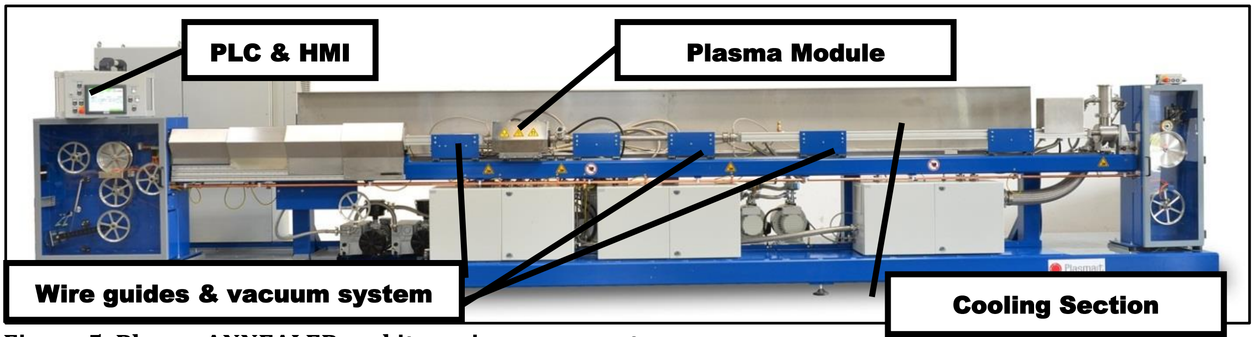

Figure 5. PlasmaANNEALER and its main components

In **Figure 5** is a photo of a plasma annealer and its main components. The plasma module and the soak/dwell section sit between two wire guides connected to the vacuum system, which maintains protective atmosphere throughout the heating and cooling zones of the machine. The purging gas can include Hydrogen, Nitrogen, Argon, Helium or their mixtures. The gas mixture is chosen to suit the application, in particular material's specific surface requirements. Usually a rapid hydrogen gas cooling system is applied in stainless steel and Nickel alloy applications. For some applications direct water cooling can be added to the last section of the cooling zone in order to reduce the total length of cooling zone. The process is controlled with PLC and touch-screen HMI, an example of which is given in **Figure 4**.

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.

The gas cooling section in the plasma annealer has a closed loop design to minimize purging gas consumption. 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.

Figure 6. PlasmaANNEALER designed for high speed annealing in-line with a drawing of fine austenitic stainless steel wire dia. 0.25mm (0.01") – 0.10mm (0.004"). A 3m long dwell section is included after the plasma heating zone to extend the annealing time.

Figure 7. PlasmaANNEALER for ultra-fine SS wire dia. below 0.1mm (0.004") for annealing in-line with drawing.

The plasma annealing plant can be built for stainless steel or nickel alloy materials with cross-sections between 0.001mm^2 (0.000001 in^2) and 300mm^2 (0.46 in^2) The process speed of the annealer depends on the material cross-section and plasma power. In some cases it is possible to install the plasma annealer in-line with a drawing machine or rolling mill depending on application and material cross-section. The annealers in the photographs in **Figure 6** and **Figure 7** have been designed for annealing in-line with drawing for fine and ultra-fine austenitic stainless steel wires.

There are two ways to install plasma annealer in-line with a fine wire drawing or rolling.
Plasma annealing can be performed immediately after drawing/rolling, which brings out degreased and extra bright finish to the annealed wire surface. Alternatively, plasma annealer can also sit in front of the drawing/rolling machine, which allows for annealed wire without the surface oxide layer to be lubricated in protective atmosphere. Immediate application of the drawing lubricant minimises the creation of surface oxides, which improves drawing and reduces the wear of the drawing dies.

There are a number of stainless steel and nickel alloy applications that benefit directly from increased annealing outputs of plasma annealing. Drawing and rolling applications where annealing can be performed in-line are of particular interest. Examples of such applications are fine and ultra-fine austenitic stainless steel wire drawing for fine weaving and knitting wire used in EMI/RFI shields, LCD/touch screens, fine printing mesh, metallic fabrics, industrial filters, demisters, airbag, and exhaust filters.

Plasma annealing has been in use for some time in applications where demanding surface requirements are important. These can be found above all in medical materials used in products such as: guide wire, stents, wire and tubes for endoscopy equipment, needles, mandrels, stylets, dental materials as well as leads and ropes of various types. Other applications with demanding surface and mechanical requirements can be found also in defence, aerospace, automotive, and oil & gas sectors to mention just a few. Plasma annealing now is increasingly adopted in mainstream applications.

A photograph of the plasma annealer for large to medium diameter wire is given in **Figure 8** The annealing line on the photograph is 30 meters (100ft) long in total and includes ultrasonic pre-cleaning unit, plasma heating section, soaking section and a gas cooling section, supported by a water based heat exchanger. The gas cooling section represents almost half of the total length of the annealing line to meet the cooling needs of a machine with a 300kg/h of production output. The plasma heating section on the other hand measures less than 2 meters. Double transport system is required to cover the full product range from 0.5mm (0.02'') to 5mm (0.2''). Such an annealer can be used as a stand-alone annealing plant in a combination with takeup and payoff.

Figure 8. PlasmaANNEALER for stainless steel and nickel alloy wire dia. 0.5mm (0.02'') to 5mm (0.2'').

In summary, plasma annealer features the following benefits when compared to the traditional tube furnace:

- Bright, scratch-free, pile-free surface finish;
- Small grain size with uniform crystal structure in longitudinal and transversal direction, which results in consistent mechanical properties and therefore reduction in:
    - drawing die wear and;
    - the number of wire breaks on subsequent drawing;
- High production speed allows plasma annealer to run in-line with drawing, rolling or sub-sequent coating processes;
- Simultaneous dry chemical-free surface cleaning through ion sputtering (i.e. degreasing and oxide removal) results in superior surface finish, ready for subsequent coating;
- High energy efficiency means considerable energy savings and lower power connection;
- Increased uptime through immediate temperature manipulation and no warming up and cooling down times;
- Low purging gas and maintenance costs compared to traditional tube furnace;
- Environment and operator friendly production;
- Compact design means short installation and commissioning times;
- Small machine footprint means a radical reduction in required workshop space per kg of output;
- Production flexibility through the ability for rapid manipulation of production parameters.

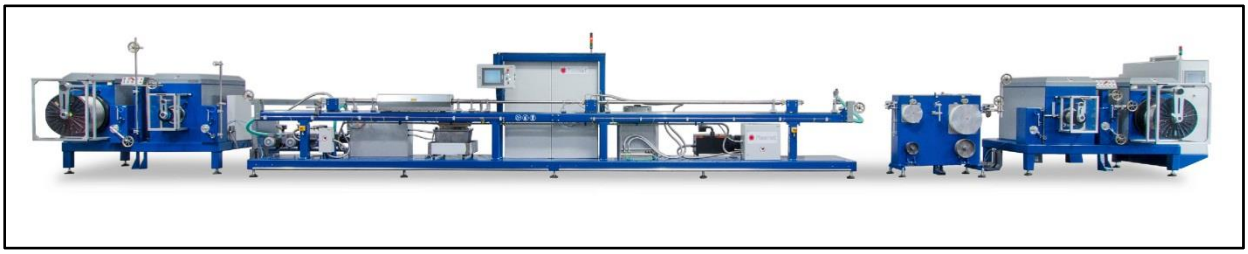

Figure 9. PlasmaANNEALER for annealing, stress relieving or degreasing of stainless steel and nickel alloy wire rope and strands dia. 0.1mm (0.004'') to 3.5mm (0.1.37'').

Figure 10. PlasmaANNEALER for annealing, and degreasing of stainless steel medical tubes.

Figure 11. PlasmaANNEALER line for nickel alloy and stainless steel wire and tubes of 0.6mm – 8.5mm OD with inlet and outlet caterpillars, double takeup (coiler + spooler).

Table 1. Comparison of the Process and the Production Parameters between the Traditional Strand Annealing Furnace and PlasmaANNEALER. (Applicable for a wide range of stainless steel and nickel alloy applications where different annealing temperatures from 800°C – 1180°C are required).

	Strand Furnace	Plasma Annealer
Process type	**Multi-line / low-speed**	**Single line / high-speed**
Production uptime	**Low (~ 70%) –** for operation at different Temperatures where cooling down & heating up is necessary	**High (~ 95%)** Immediate start and stop
Investment in furnace	**Low**	**High**
Investment in payoffs & takeups	**High** – multiple lines	**Low –** single line
Power /Energy usage per ton	**High –** especially high at underutilization **(15% - 50% energy efficiency)**	**Low -** irrespective of utilization **(~ 80% energy efficiency)**
Purging gas usage per ton	**High** – especially high at underutilization	**Low –** irrespective of utilization
Labour cost per ton	**Similar** when off-line annealing	**Lower** when in-line with drawing
String-in time	**Long** – multiple lines	**Short** – single line (larger spool size)
Maintenance cost per ton	**High** – cost of Ni tubes/downlime	**Low**
Purging gas supply	**Expensive** gas installation required	**Low cost** can be supplied out of bottles
Power connection required	**Large –** approx. 2-4 times larger than PA	**Small**
Install. & Commissioning time	**Long**	**Short –** average. 3-5 days
Production line footprint	**Large**	**Compact**
Annealing power/temp. control	**Limited / slow change in T**	**Accurate and immediate**
Working capital locked in material	**High –** multiple spools	**Low –** single spool

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Primoz Eiselt is the founder of Plasmait GmbH and company's Managing Director. Primoz has pioneered plasma technology for continuous applications in the metal wire and tube industry. He claims over 75 industrial installations of continuous plasma treatment lines worldwide. Together with his team he holds three patents related to plasma technology. Primoz graduated from TU Graz, Austria, and obtained MSc in Physics.

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