HEAT TREATMENT

Heat treatment for the production of electrical tubular heating elements

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Tubular heating elements are electrical heating elements which consist of a thin resistance wire built as a fine spiral, which is placed central in a protection tube made of metal. The tube is filled with a insulating compound. This basic principal configuration was already patented in USA in 1859. More than half a century passed until this idea could be used comercially. The following explains the manufacturing of tubular heating elements. Furthermore, the report is comparing annealing systems with innovative heat treatment systems which are used to produce the tubular heating elements.

In 1918, a patent was granted to General Electric USA. The subject was a metal-coated round element filled with insulating powder and through which a resistance wire was drawn in the center. This element was positioned by pressing and rolling. After that, the element could be shaped into any desired form without changing the electrical and thermal properties. Once the resistance wire was positioned, there was no longer any risk of short-circuiting between the inner wire and outer sheath, and the possibility of achieving uniform temperatures throughout the entire tube was significantly improved.
The Norwegian Christian Backer received a patent in 1921 for the conversion of pure metallic magnesium to magnesium hydroxide by adding water vapor under high pressure and further conversion to magnesium oxide through heat treatment. From the electrically conductive magnesium metal, an excellent insulating compound was thus created. The subsequent patent in 1926 by Christian Backer concerned the manufacture of electric tubular heating elements as an alternative to stove plates with fuel heating.
Christian Backer emigrated to Canada and developed a complete production facility for tubular heating elements in Ottawa. After World War II, Christian Backer returned to Scandinavia and founded Backer Elektro-Värme AB in Sösdala, Sweden in 1949. The electric tubular heating element became internationally known as the so-called "Backer element."
In Illinois, USA, from 1945 to 1955, Mr. Sterling A. Oakley and others developed machines for winding the heating conductor wires, manufacturing connection bolts, filling the sheath tubes with magnesium oxide powder while simultaneously placing the heating conductor, and rolling mills for reducing the filled tubes. Through compression, the heating coil is centrally embedded with highly compressed MgO powder. This results in ideal heat conduction to the tube sheath as well as optimal electrical insulation values.
Kanthal AB in Hallstahammar, Sweden, received the license from the Oakley Company in 1955 for the use of patents for all machines for manufacturing tubular heating elements. The agreement was valid worldwide except for the USA and Canada with patent protection until 1980.
Fig. 1 shows the essential components of tubular heating elements. Tubular heating elements are manufactured as electric heating elements in many different designs regarding size, shape, electrical power, materials, etc., depending on the application. The outer diameter of the tube sheath is typically in the range of 3.0 to 16.0 mm and the tube length ranges from 200-8,000 mm.
The materials for the tube sheath are:

- Aluminum
- Copper
- Carbon steel
- Austenitic Cr-Ni steel
- Ferritic Cr-Ni steel

- High-temperature resistant steel
- Nickel-based alloys
- Titanium
- Special materials

The selection is made according to the stress requirements regarding resistance to temperature, corrosion, scaling, and strength.

By far the largest application area for tubular heating elements is household appliances. For this purpose, several million pieces are produced daily worldwide with tube diameters of 6.5 or 8.5 mm × 1,000 to 2,000 mm length and tube sheaths made of rust and acid-resistant stainless steels. While previously the dimensions with a diameter of 8.5 mm dominated, the 6.5 mm diameter has predominated for several years. The thinner tubular heating element is lighter, weighing only 0.15 kg/m instead of 0.24 kg/m, and manufacturing is correspondingly much more cost-effective.

The application areas for tubular heating elements are extremely diverse for direct heating of liquids and gases as well as contact heating, where the tubular heating elements are cast in metals. The heated liquids are predominantly stationary or flowing water but also oil, chemicals, tar, salt baths, or lead baths. For heating gases, this particularly includes stationary or flowing air as well as radiant heating using reflectors. Important areas include water heating in household appliances, cooking and grilling applications, space heating, sauna heaters, steam generators, railway car heating, switch de-icing, etc.

Heat Treatment

The various manufacturing steps for producing tubular heating elements also include heat treatment. The annealing process becomes necessary because the cold forming through rolling of the tubular heating elements results in considerable work hardening. This hardening is undesirable because the tubular heating elements must usually be easily bendable for their intended use (Fig. 2), and even with extreme shaping (Fig. 3), no cracks should occur in the tube sheath.

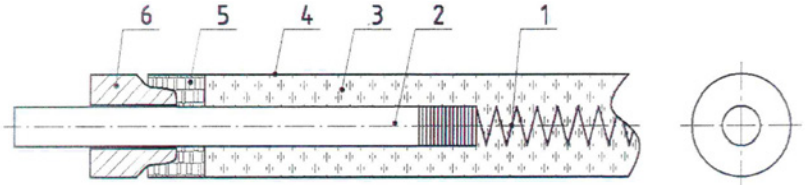

Figure 1: Structure of a tubular heating element: 1. Heating conductor; 2. Connection bolt; 3. Insulating compound; 4. Tube sheath; 5. Sealing compound; 6. End sleeve
Source: FK Industrieofenbau + Schutzgastechnik GmbH

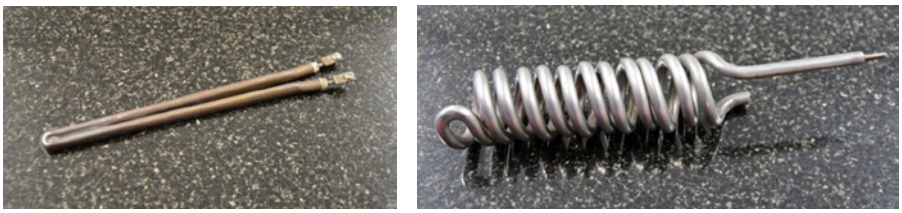

Figure 2: Bendability of annealed tubular heating elements
Source: FK Industrieofenbau + Schutzgastechnik GmbH

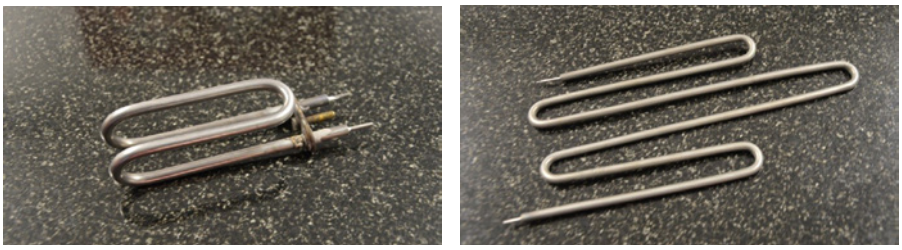

Figure 3: Typical shaping
Source: FK Industrieofenbau + Schutzgastechnik GmbH

Depending on the tube diameter, minimum bending radii according to Table 1 are achieved for CrNi materials.

During rolling of the tubular heating elements, the diameter of the tube sheath is reduced by 10-20 %, resulting in an elongation of the tube by 8-33 %. Through the compression of the rolling process, the MgO powder is compacted to over 3.10 g/cm^3. After filling the MgO powder using vibration machines, the original density is approximately 2.40 g / cm^3. This improves the thermal conductivity for transferring heating energy from the heating coil to the tube sheath from 3.4-7.5 Wm^{-1}K^{-1}. At the same time, the compression provides stable centering of the embedded heating coil.

The heat treatment is recrystallization annealing, where the material structure displaced by the rolling process is returned to its original state, thus reversing the hardening. The annealing temperatures vary according to the material of the tube sheath. For aluminum, heating to 480 °C is sufficient, while copper requires about 650 °C. Tubular heating elements made of carbon steels are heat treated in the range of 800-900 °C, and highly alloyed tube sheaths require annealing temperatures of 1,000-1,100 °C.

For a satisfactory result of the heat treatment, the tube sheath must be completely heated through at the specified annealing temperature. The time for temperature equalization in the tube wall is only one minute due to the very small wall thicknesses. Longer holding times do not provide better properties for the annealing result.

Heat treatment is always carried out under protective gas atmosphere. Otherwise, the tubular heating elements

Table 1: Minimum bending radii
Source: FK Industrieofenbau + Schutzgastechnik GmbH

Tube Sheath Ø (mm)	Min. Bending Radius (mm)
3	4
6,5	10
8,5	12
11,5	20
16	25

would oxidize inadmissibly due to the oxygen in the air.

New Continuous Annealing System

For the heat treatment of tubular heating elements, FK Industrieofen + Schutzgastechnik GmbH developed a new furnace system specific to this application. The FK process offers numerous advantages over conventional annealing systems where tubular heating elements are transported through the furnace on belts, wire mesh belts, chains, or sleds. Due to the technical advantages and especially the economic efficiency, over 50 annealing systems based on the new principle have been installed worldwide. Compared to conventional annealing processes, the total costs for heat treatment of tubular heating elements are more than halved.

In the FK process, the tubular heating elements are pushed through the annealing furnace by means of a drive station located in front of the furnace. Each tubular heating element pushes the previously loaded tubular heating element ahead of it. The annealing and cooling channel of the furnace system consists of a multitude of tubes, the number of which is determined by the required throughput capacity. The inner diameter of the annealing and cooling tubes is dimensioned so that only one tubular heating element can be pushed through at a time. Standard furnaces are designed with two to 30 parallel channels. This results in annealing capacities of 5-300 kg/h net or correspondingly 20-1,250 m/h of stainless steel tubular heating elements with 8.5 mm diameter.

Fig. 4 shows the overall view of a continuous annealing system with protective gas equipment for heat treatment of tubular heating elements with a throughput capacity of 200 kg/h net, according to the FK process.

Since the conventional transport devices are eliminated for conveying the tubular heating elements through the furnace system, the annealing process takes place without the usual dead loads. This alone reduces the energy requirement by about 50 % for the same net throughput capacity. Accordingly, the required cooling capacity for cooling the tubular heating elements to approximately 50 °C is also reduced. Furthermore, indirect water cooling of the cooling channels is only recommended for throughput rates exceeding 150 kg/h. The multitude of cooling tubes results in a large heat dissipation surface, so ambient air is sufficient for cooling.

A special feature is the sealing at the outlet openings of the cooling tubes by means of elastic rings to the tubular heating elements. Cooling and annealing tubes are connected gas-tight to each other and are constantly kept under protective gas. Conventional furnace systems with annealing muffles and cooling channels require large cross-sections at the inlet and outlet sides because the conveyor belts or other transport devices must be passed through. A gas-tight seal at the outlet side is therefore not possible. The consumption of protective gas in these annealing furnaces is up to 50 times higher than with the FK process. The need for protective gas is also a significant cost factor. Additionally, the push-through tubes of the new annealing systems can be simply sealed gas-tight at the inlet and outlet sides with caps (Fig. 5).

Figure 4: Annealing furnace according to FK process
Source: FK Industrieofenbau + Schutzgastechnik GmbH

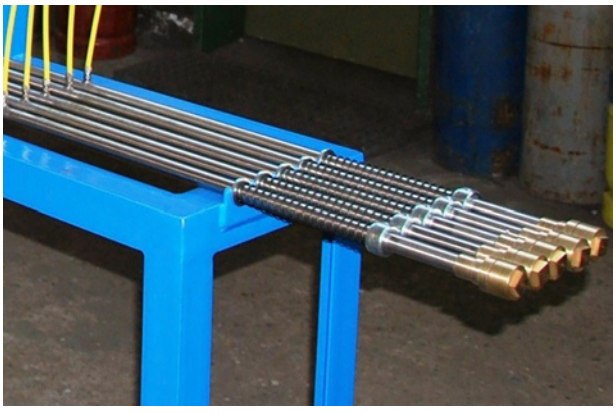

Figure 5: Gas-tight sealed push-through tubes
Source: FK Industrieofenbau + Schutzgastechnik GmbH

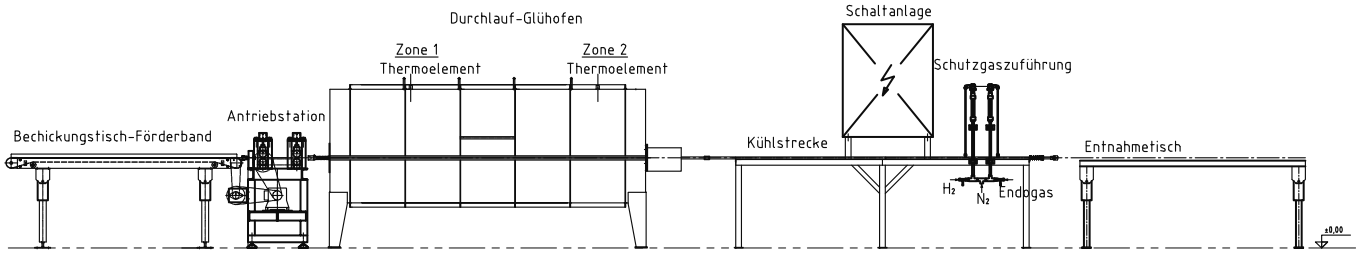

Figure 6: Longitudinal view of the continuous annealing system

Source: FK Industrieofenbau + Schutzgastechnik GmbH

Thus, even with shift operation, heat treatment with perfect surfaces is guaranteed, i. e., also bright annealing of stainless steel tubular heating elements with hydrogen atmosphere. Conveyor belt annealing furnaces, on the other hand, require three-shift operation for bright annealing of highly alloyed sheath tubes. Every shutdown of these furnaces requires elaborate purging with protective gas. Furthermore, these annealing furnaces are very sensitive to drafts in the production hall, and when using hydrogen as furnace atmosphere, the relatively large volume in the annealing muffle and cooling channel creates a corresponding safety risk. It should also be noted that the supplied protective gas must be heated to annealing temperature in the furnace, requiring heating energy.

For an economic consideration, the costs for wear parts and maintenance are naturally also of great importance. Transport devices, e.g., conveyor belts, are subjected to extreme stresses because these components are heated to over 1,000 °C when passing through the annealing zones and then cooled back to room temperature in the subsequent cooling zone. This stress load repeats constantly on the long conveyor belts, so high-temperature resistant materials are subject to rapid natural wear. The high-quality annealing muffles are also heavily stressed and must be replaced or repaired due to deformation. The replacement of wear parts is time-consuming and cost-intensive. Not least, the investment costs for purchasing a conventional annealing system are about twice as high as those of the innovative heat treatment furnaces with the same throughput capacity.

The complete structure of a continuous annealing system of medium size with 10 annealing channels is shown in Fig. 6 in longitudinal view and in Fig. 7 in cross-section for illustration. The detailed description of the individual assemblies in the direction of flow begins with the loading table. The loading table serves to store the tubular heating elements that are to be subjected to annealing treatment and automatically feeds the tubular heating elements into the drive station. For this purpose, the loading table is designed as a conveyor belt with an endless belt made of smooth plastic fabric and side guide rails. The length of the loading table is selected in coordination with the maximum lengths of the tubular heating elements.

A separate drive is not required for the conveyor belt. The conveying speed is transmitted to the conveyor belt of the loading table from the downstream drive station by means of a chain connection. The chain drive is designed so that the speed on the loading table is always 10 % faster than the variably

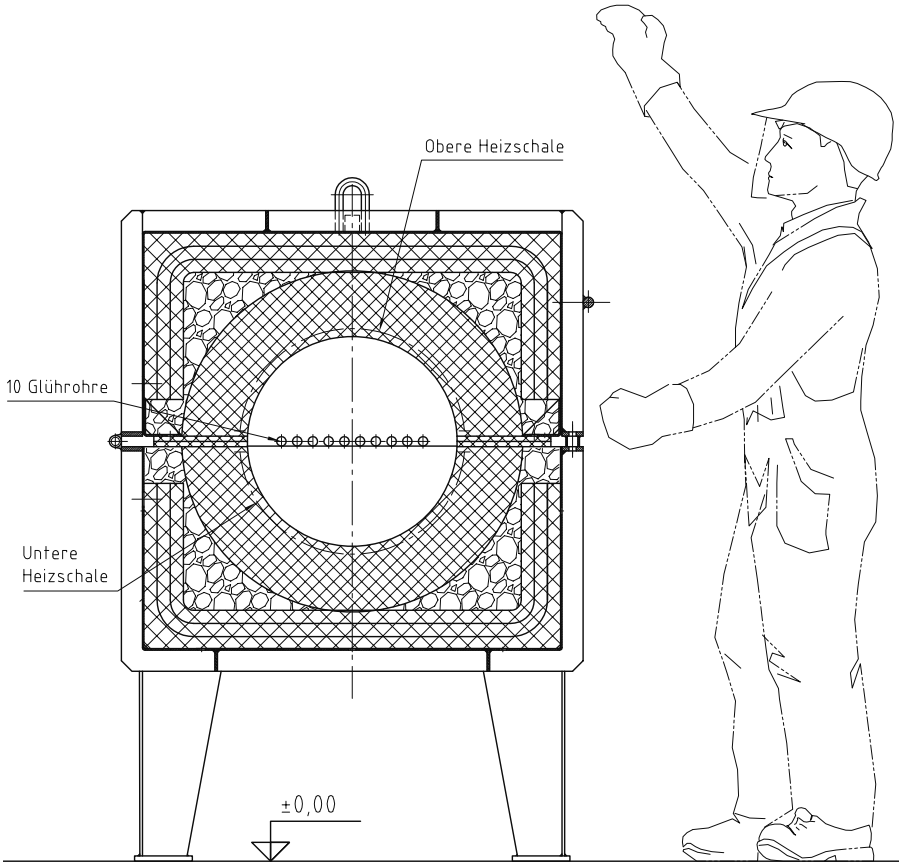

Figure 7: Cross-section of the continuous annealing system

Source: FK Industrieofenbau + Schutzgastechnik GmbH

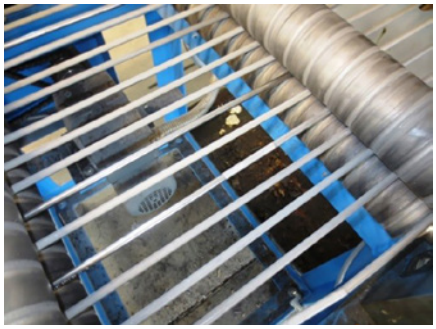

Figure 8: Drive rollers for straight guidance of tubular heating elements
Source: FK Industrieofenbau + Schutzgastechnik GmbH

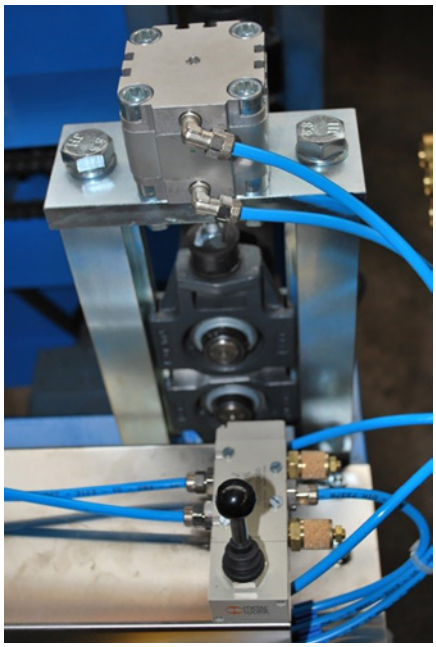

Figure 9: Pneumatic pressing of the drive rollers
Source: FK Industrieofenbau + Schutzgastechnik GmbH

Figure 10: Two-part furnace housing
Source: FK Industrieofenbau + Schutzgastechnik GmbH

pre-programmed throughput speed of the furnace. This measure ensures that the tubular heating elements are safely introduced into the drive rollers of the drive station. An essential component of the drive station is two drive roller sets arranged one behind the other. A drive roller set consists of rubber-coated rollers with guide grooves for straight guidance of the tubular heating elements (Fig. 8).

Only the lower rollers are driven via chains and are not height-adjustable. The upper drive rollers are pressed down with pneumatic cylinders (Fig. 9). The contact pressure can be adjusted to requirements by setting the air pressure. To adjust the conveying speed, the gear motor is controlled via a frequency converter. This allows the speed to be electronically adjusted steplessly in the range of 1:10 from the control system.

In the heat treatment system, the actual annealing furnace has a heating chamber with two control zones of 750 mm useful length each. The furnace is equipped with 10 annealing channels made of seamless tubes in high-quality nickel-based alloy with oxidation resistance up to 1,150 °C. This high-temperature resistant material is not subject to sigma phase embrittlement. In the heating chamber, the annealing tubes are supported at intervals of about 250 mm by vertically installed refractory plates. Furthermore, the annealing tubes are pulled by means of a spring tensioning device at the furnace outlet so that the annealing tubes remain exactly straight. This also simultaneously relieves the length increase of the annealing tubes of approximately 40 mm caused by thermal expansion.

A special feature is the electrical heating system of the furnace. Above and below the annealing tubes, the special heating elements are arranged for free radiation. The heating coils made of resistance wire are integrated on the surface in vacuum-formed modules made of ceramic material.

Through the all-around heating of the annealing tubes with sensible arrangement of the circular, radiating heating surfaces, uniform temperature fields are achieved in the furnace chamber. PtRh-Pt type thermocouples are used as temperature sensors to ensure the required accuracy and safety at furnace chamber temperatures of 1,100 °C. For precise control of the furnace temperature, software PID controllers with continuous output are provided. The heating elements receive stepless energy supply in connection with a thyristor power controller. With this concept, a control accuracy of ±1 K is achieved.

The vacuum-formed heating modules also serve as effective thermal insulation because the ceramic material with a density of 0.2 kg/dm³ is very light. Optimal thermal insulation is achieved by using the most modern microporous insulating materials as back insulation. The steel shell of the furnace housing therefore has only a temperature of approximately 20 °C above ambient air at working temperatures up to 1,100 °C in the useful space of the annealing furnace. Due to the lightweight construction of the inner lining, the furnace system can be brought from 20 °C to operating temperature in less than one hour.

The furnace housing is divided into two parts and separated horizontally at the level of the annealing tubes. Via a hinge on the longitudinal side, the upper half of the furnace housing together with the complete lining with heating system can be simply folded up. This provides practical access for inspections of the furnace interior with heating and annealing tubes (Fig. 10).

Behind the heated furnace section is the cooling section consisting of 10 cooling tubes, the base frame, equipment for supplying protective gas, and the control cabinet. Seamless tubes made of stainless steel are sufficient for the cooling tubes. The gas-tight connection to the high-quality annealing tubes is made by a sleeve and brazing (Fig. 11). As a guideline, the cooling section is twice as long as the heated furnace

space. If the installation space is limited, the cooling tubes can be placed in a water bath. This significantly shortens the cooling section, i. e., the length is halved.

Protective Gas Supply

The heat treatment system shown was designed for bright annealing of tubular heating elements made of CrNi steel. To avoid unwanted oxidation and achieve metallically bright surfaces of the tubular heating elements, high requirements are placed on the purity of the protective gas atmosphere. Oxidation from 250 Ångström layer thickness becomes visible through dull or discolored appearance of the tube sheath. Hydrogen with low moisture and residual oxygen content is used as protective gas. The permissible content of water vapor in the protective gas is determined by the equilibrium relationship between the ratios of H_2/H_2O and metal/metal oxide. The dew point must be lower than the most active alloying element of the tube sheath (Fig. 12). Decisive for achieving the brightest possible surface when annealing tubular heating elements made of CrNi steel is the dew point of the protective gas. The supplied hydrogen should therefore have at least a dew point of -60 °C corresponding to a moisture content of maximum 10 ppm H_2O (0.001 vol.%). The hydrogen is fed in near the outlet side of the cooling section. A micro-dosing valve is installed in the supply line for each cooling tube so that the gas quantities can be precisely adjusted. Furthermore, the entire protective gas quantity can be read on a float-type flow meter. Since the cooling tubes are hermetically sealed at the outlet ends, the hydrogen flows against the conveying direction of the tubular heating elements through the entire furnace system and is flared at the inlet side of the annealing tubes. While the hydrogen in the holding and equalization zone assumes the set furnace chamber temperature and acts reductively on the CrNi tubular heating elements, the protective gas removes impurities brought in by the annealing material in the heating zone of the furnace. Impurities mean moisture and air oxygen adhering by adhesion. The consumption of hydrogen is extremely low and amounts to only 0.2 Nm^3/h in total for the heat treatment system with a throughput capacity of 60 kg/h net. When purchasing hydrogen in compressed gas cylinders with 50 l geometric volume and filling pressure of 300 bar, the gas filling quantity is about 13 Nm^3. This means that a single steel cylinder can supply the annealing furnace for 65 production hours. The cylinder pressure is reduced to the working pressure of approximately 50 mbar with a 2-stage gas pressure reducer.

Safety Equipment

When annealing with hydrogen as furnace atmosphere, careful safety measures must be taken. The ignition range of hydrogen in combination with air is particularly wide at 4-75 %. Additionally, the lower limit for ignition temperature is very low at 510 °C. Advantageous, however, is that with the FK process, only an extremely small space is filled with hydrogen. The useful volume in annealing and cooling tubes amounts to only about 0.003 m^3 in total for medium furnace size. Nevertheless, some interlocking devices and safety circuits are provided that exclude absolute risks even in case of incorrect operation. A solenoid valve in the supply line for hydrogen can only be opened when a temperature of 750°C is reached in the furnace chamber. Furthermore, a fully automatic nitrogen purging equipment is installed on the furnace system. A high-pressure cylinder with nitrogen is connected so that in case of malfunctions or interruption of the hydrogen supply, the purging process of the annealing and cooling tubes is initiated. The purging system also works automatically in case of power failure through a normally open solenoid valve. Even during startup and shutdown of the annealing furnace, safe protective gas operation is ensured by purging with nitrogen. The last component of the heat treatment line is the discharge table connected behind the cooling section. The discharge table consists of the

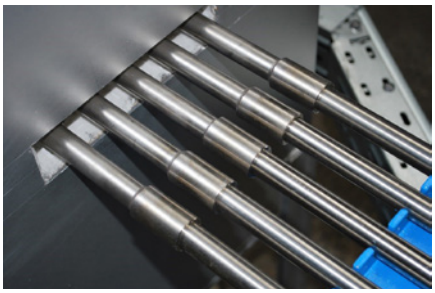

Figure 11: Connection of annealing/cooling tubes
Source: FK Industrieofenbau + Schutzgastechnik GmbH

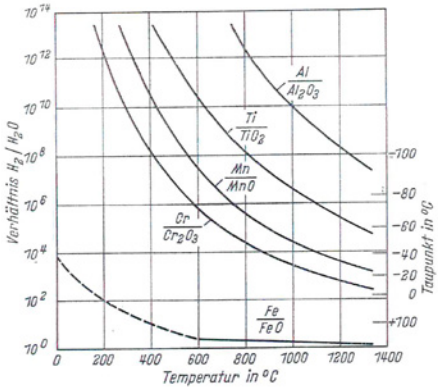

Figure 12: Temperature/dew point function of various metal/metal oxide equilibria
Source: FK Industrieofenbau + Schutzgastechnik GmbH

Figure 13: Control system with process visualization
Source: FK Industrieofenbau + Schutzgastechnik GmbH

Table 2: Comparison of the FK process to conveyor belt continuous furnace for bright annealing with a capacity of 100 kg/h net CrNi tubular heating elements

Source: FK Industrieofenbau + Schutzgastechnik GmbH.

Aspect	FK System	Conveyor Belt Continuous Furnace
Annealing channels	10 annealing and cooling tubes	1 muffle 300 mm useful width
Shift operation	Yes	Not possible
Heating time of cold furnace to operating temperature	1h	10h
Bright surface after start of protective gas operation	< 1h	> 24h
Electrical energy requirement	30 kW	63 kW
Protective gas consumption	0.2 Nm^3/h	10 Nm^3/h
Cooling water consumption	0	3 Nm^3/h
Investment costs - guideline for purchase (2017)	€ 120,00	€300,000 including protective gas generator
Installation & repair costs - guideline values	€3,000/year	€15,000/year

base frame with a table top made of stainless steel sheet with lateral flanges. The length is practically designed to match the dimensions of the loading table. The tubular heating elements conveyed through the furnace system and fully annealed are pushed onto the smooth table top and can be taken from there for further processing.

The measuring and control system of the continuous furnace is installed in a control cabinet that is arranged space-savingly on the base frame of the cooling section. The entire heat treatment system with the process sequence is visualized with the TFT wide screen color display (Fig. 13). All process data such as temperatures, throughput speed, etc. are displayed and continuously recorded. This ensures quality management and product liability. Fault messages and errors are automatically recorded in the data storage. Optionally, a remote system for remote diagnosis of the heat treatment system can be set up.

Flexibility

The FK process is not only specifically suitable for bright annealing of tubular heating elements but can also be effectively used for dark annealing. When tubular heating elements are used as radiant heaters, the dark surface improves radiation, and in sauna heaters, the discoloration serves as a protective layer. In dark annealing, a uniform oxide layer must be generated. Tube sheaths made of CrNi steel form a dark green chromium oxide layer under certain protective gas atmospheres during annealing. The required protective gas can be produced cost-effectively in the area of the furnace system by catalytic partial combustion from natural gas or propane. There is even the possibility of simultaneously producing bright tubular heating elements in some annealing channels and parallel dark surfaces in one furnace system. For this purpose, each annealing channel receives multiple supplies for different protective gases.

The annealing and cooling tubes are also suitable for tubular heating elements with different diameters. For example, tubular heating elements with 6.5, 8.5, and 11.5 mm diameter can be conveyed through the furnace at the same time. However, the tubular heating elements with the largest diameter determine the transport speed and thus the annealing time. The individual annealing channels can thus be assigned to different tasks as desired, and individual channels can also be completely shut down as needed. In connection with the short time for setting the desired working temperature, an extremely flexible and universal heat treatment system for tubular heating elements is obtained.

Table 2 shows a comparison of the FK process to the conventional conveyor belt continuous furnace for bright annealing of CrNi tubular heating elements. The comparison of consumption data for these furnaces shows what cost savings occur in annealing treatment. The capital expenditure is also favorable, resulting in short amortization periods.

Conclusion

A heat treatment system for electric tubular heating elements is presented in detail and all construction details are thoroughly explained. Very special features are the high energy efficiency as well as the minimal protective gas requirement. In addition, there is the flexibility of the system with achievement of optimal annealing results.

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