Heat Treatment in Additive Manufacturing

With more than 60 years of experience in the construction of industrial furnaces, Nabertherm also manufactures furnaces that are designed for the heat treatment of components produced using additive manufacturing. This article provides an overview of different types of heat treatment for additive manufacturing and presents the main furnaces types for this.

Introduction

Many methods of additive manufacturing require subsequent heat treatment of the manufactured components. The furnace requirements with respect to the heat treatment depend on the component material, working temperatures, the atmosphere in the furnace and, of course, the additive manufacturing method.

Based on the temperature, furnaces can be divided into four groups. The temperature range up to 300 °C is covered by ovens and chamber dryers, with which moisture can be removed from the batch. Up to 850 °C, air forced convection ovens are used, which transfer heat to the batch using an air circulation. Above 850 °C, heat radiation is used for the transfer of heat. These annealing furnaces can reach a maximum temperature of 1200 °C. High-temperature furnaces, with maximum temperatures of 1200 °C to 1800 °C, require insulation materials and heating elements tailored to these temperatures. Since the furnaces of each group are optimally designed for their operating temperature range, they should not be used outside this range.

I. Ceramics

1. Drying

Powder-based printing methods require a constant quality of the powder. Hard moisture that is absorbed by the powder during storage can lead to deterioration in the quality of the manufactured component. Drying at low temperature provides for removal of the residual moisture from the powder. Drying ovens, which are available in different sizes and for temperatures up to 300 °C, are suitable for this purpose.

2. Debinding

After additive manufacturing with the addition of binders, such as after binder jetting, the binder is expelled by heat treatment. The binder consists of organic compounds and can create an explosive atmosphere in the furnace due to its flammability.
Therefore, fresh air needs to be continuously supplied to the furnace during binder removal in air in order to dilute the concentration of the vaporized binder in the furnace. As protection for the employees, safety concepts for debinding must be provided in the oven. The safety concept depends on the amount of organic material, the evaporation rate, and the temperature range in which the binder is expelled.

With a passive safety concept, the user must set the process in such a manner that the maximum permitted evaporation rate is not exceeded. The furnace monitors all the important safety functions and initiates appropriate action in case of a malfunction. This safety concept is recommended when the evaporation rate is known, such as in repeating production processes.

With changing needs or large amounts of binder, an active safety concept is recommended. Here, a probe monitors the binder concentration and regulates the amount of fresh air needed. If the furnace is operated above its performance limit, appropriate malfunction measures are carried out automatically.

3. Sintering
After debinding, the components must be sintered in order to ensure high rigidity and shape stability. In combi furnaces, which allow debinding and subsequent sintering in the same furnace, the temperature is raised to the sintering temperature after debinding. Loading from a debinding furnace into a sintering furnace is not necessary because both process steps are carried out in the same furnace in one run.

II. Metals

1. Debinding
As described for ceramics, debinding of metals is also necessary after binder jetting. For the heat treatment, metallic components require an atmosphere with reduced oxygen content. Many processes can be implemented with a gas supply box in an air circulation furnace. During the heat treatment the gas supply box, made of heat-resistant metals, is flushed with non-flammable protective or reaction gases such as nitrogen or argon. The achievable residual oxygen content is less than 3% by volume. The maximum permissible temperature during debinding is 650 °C.

For applications which require a lower content of residual oxygen, hot-wall retort furnaces are used. The residual oxygen content of 0 ppm can be achieved. The maximum temperature in the retort furnace during debinding is 600 °C. Furnaces with gas supply box as well as hot-wall retort furnaces can be used for low and high amounts of organics.

<table>
<thead>
<tr>
<th>Concept</th>
<th>Resid. oxygen cont.</th>
<th>Level of organic matter</th>
<th>Tmax in °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>With gas supply box</td>
<td>&lt; 3 % by volume</td>
<td>Low to high</td>
<td>650</td>
</tr>
<tr>
<td>Retort furnace</td>
<td>0 ppm</td>
<td>Low to high</td>
<td>650</td>
</tr>
</tbody>
</table>

2. Sintering
In most cases, the sintering of metal components that have undergone debinding takes place using non-flammable protective or reaction gases such as nitrogen or argon, or in a vacuum, in order to prevent the oxidation of the components. The required optical and mechanical quality requirements for the components determine the permissible residual oxygen content and the type of oven.

Nitrogen is inexpensive to purchase and is suitable for the treatment of copper, for example. Since titanium, cobalt-chromium and stainless steels store nitrogen in their surfaces during heat treatment, these metals require argon as a protective gas. During heat treatment, the furnace is continuously flushed with protective gas.

Chamber furnaces with gas supply boxes can also be used for sintering in many cases. The maximum temperature is limited to 1150 °C and a residual oxygen content of < 3% can be achieved.

If this leak rate is insufficient, hot-wall retort furnaces can be used up to 1150 °C. In these furnaces, a residual oxygen content of 0 ppm can be achieved. These furnaces can also be used under vacuum up to a temperature of 650 °C.
Due to the high temperatures that are often necessary for sintering, cold-wall retort furnaces can be used for this application. These models allow operation under protective gas up to 3000 °C or vacuum operation up to 2400 °C. When they are equipped with a safety package, all retort furnaces can also be operated using hydrogen in order to reduce oxidized component surfaces. The comprehensive safety package includes, among other things, a nitrogen container for emergency purging of the oven compartment in case of failure, a waste gas torch for burning the hydrogen, necessary sensors and a safety PLC control.

### 3. Stress Relief Annealing

Due to the high selective heat input during additive manufacturing, components that are produced using melting methods without a binder must undergo stress relief annealing after printing. Methods that melt the powder during printing include Selective Laser Melting (SLM), Selective Laser Sintering (SLS), and Electron Beam Melting (EBM). Since the temperatures for stress relief annealing are lower than for sintering, the protective gas atmosphere can be generated in a retort furnace or a chamber furnace with a gas supply box. Sealing a chamber furnace instead of using a gas supply box is also possible. The residual oxygen content is 200 - 500 ppm in a sealed furnace, below 200 ppm in a protective gas box and 0 ppm in a retort furnace. Below 700 °C, retort furnaces offer only a slow heat transfer to the batch since the heat radiation is low. The heating and cooling times are longer compared to the protective gas atmosphere.

<table>
<thead>
<tr>
<th>Concept</th>
<th>Residual O₂ content</th>
<th>Atmosphere</th>
<th>Tmax in °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sealed furnace</td>
<td>200 - 500 ppm</td>
<td>Nitrogen, argon</td>
<td>1700</td>
</tr>
<tr>
<td>Protect. gas box</td>
<td>&lt; 200 ppm</td>
<td>Nitrogen, argon</td>
<td>1150</td>
</tr>
<tr>
<td>Hot-wall retort furnace</td>
<td>0 ppm</td>
<td>Nitrogen, argon</td>
<td>1150</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hydrogen</td>
<td>1150</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vacuum</td>
<td>2400</td>
</tr>
<tr>
<td>Cold-wall retort furnace</td>
<td>0 ppm</td>
<td>Nitrogen, argon</td>
<td>3000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hydrogen</td>
<td>1800</td>
</tr>
</tbody>
</table>
III. Plastics and Waxes

Additive manufacturing is also used in investment casting to produce lost models made of wax or plastic. After creating the lost wax models using Wax Deposition Modeling (WDM), ceramic coatings are applied and the model – including the coating – is placed in the dewaxing furnace. The lost models are dewaxed or burned out. Electrically heated furnaces that remain below the flash point of the wax can be used. The wax melts out completely and is collected in a heated container under the furnace. Furnaces that operate above the flash point of the wax are gas-heated and reach 850 °C. A portion of the wax is melted out and collected in the container. The remaining portion is vaporized and combusted in the furnace.

Since the wax models require expensive injection molds and wax presses, additively produced plastic models made of polymethylmethacrylate (PMMA) are being used more and more. As a result, wax models can be substituted economically, and complex shapes can be realized. After the additive manufacturing step, the PMMA models are impregnated with wax to produce a smooth surface. The further procedure corresponds to that of the wax model. Above 73 °C, the PMMA’s shape is no longer stable and it ignites at about 700 °C without leaving any residue. To ensure safe combustion, one of the safety packages for debinding described above is required for the stove that is used.

The curing of components made of plastics that are not used as a lost model but as a final product also takes place using heat treatment in the furnace. Since this curing process takes place at low temperatures, drying ovens and chamber dryers with a maximum temperature of 300 °C are used.

IV. Summary

Heat treatment is an important component of the additive manufacturing process and must be considered when purchasing machinery to be used for additive manufacturing. The selection of a suitable furnace depends on the temperature, the additive manufacturing process that is used, the material of the component, and the type of heat treatment.

As one of the world’s leading manufacturers of standard furnaces and customized furnace concepts, Nabertherm can provide the furnace concept required for the specified process, including for the heat treatment of components made using additive manufacturing.

After detailed consultation with the customer, Nabertherm project engineers determine the requirements and right concept for the heat treatment. The customer receives a furnace that is perfectly tailored to their processes so that they can reliably produce their products with the desired quality.

V. Information about Nabertherm GmbH

- Product groups: industrial and laboratory furnaces, from 30 °C to 3000 °C
- Quantity: 7,500 per year
- Founded: 1947
- Number of employees: 450
- Headquarters and production site: Lilienthal (near Bremen, Germany)
- Distributors:
  - Nabertherm Inc. (USA)
  - Nabertherm Schweiz AG (Switzerland)
  - Nabertherm SARL (France)
  - Nabertherm Shanghai Ltd. (China)
  - Nabertherm Ltd. (UK)
  - Nabertherm Italia (Italy)
  - Nabertherm Iberica (Spain)
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