CONTINUOUS HIGH-TEMPERATURE ANNEALING OF HIGH PERFORMANCE COPPER ALLOYS
Continuous high-temperature annealing of high performance copper alloys

The launch of strip flotation furnace technology by OTTO JUNKER in around 1970, with the installation of the world’s first such plant at Stolberger Metallwerke in Germany, brought a revolutionary advance in annealing output to continuous annealing lines processing copper and brass strip without physical contact. Until then, the continuous annealing process had been dominated by catenary type furnaces [1]. This revolution owed its success to two main factors:

1. The high-convection flow employed, which also for the air cushion supporting the strip, can provide a much greater heat transfer than the radiant heating system of a catenary type furnace. Accordingly, the achievable annealing output for a given shop space or line length is clearly increased.

2. Catenary type furnaces involve very high levels of strip tension, depending on the catenary sag depth – a fact that imposes severe limits on the system’s length. By eliminating the sag, it became possible to achieve much longer furnaces in addition to gains in heat density (see item 1).

Strip flotation furnaces thus came to outperform the previous catenary type furnaces on two counts, and by a considerable margin.

A concurrent development at the time, albeit initiated somewhat earlier, consisted in the use of high-convection vertical furnaces, which attained heat transfer rates and design lengths similar to those of horizontal strip flotation systems. This was true particularly in the U.S. and Japan where the resulting building heights were viewed less critically; in Japan, the use of vertical space was even considered to some extent advantageous over horizontal floorspace demand.

In Europe, the principle of horizontal strip flotation prevailed. Apart from the advantage that such horizontal lines can be installed in shops of ‘normal’ height, an additional benefit lies in better accessibility for maintenance or strip threading operations.

Progress in strip flotation furnace technology has been keeping pace with market requirements. While the first such furnaces had a temperature limit of 750°C and could process strip up to a maximum gauge of approx. 1.5 mm with the use of a protective gas atmosphere being optional at best, we can now anneal strip measuring up to 2 mm in thickness at 850°C reliably and to a scratch-free finish [2]. With thinner material, it is even possible to attain 900°C [3]. The use of forming gas containing up to 5% hydrogen has become standard today, but numerous plants using significantly higher hydrogen levels have been realized as well [4].

On the other hand, both a higher hydrogen content and a higher temperature must be compensated for by the flotation system since both effects diminish the density of the air (or forming gas) and thereby reduce its buoyancy.

An additional, much more critical effect at elevated temperatures is the temperature resistance limit or long-term creep strength of the recirculation fans. A temperature rise from 800°C to 900°C will already cut the creep rupture strength of the high-performance materials employed by more than 50%; a rise from 900°C to 950°C will cause a further 40% drop [5].

However, recently developed copper alloys, especially high-strength types with a particularly good relaxation behaviour (so-called high-performance or „HP“ alloys) may require annealing at up to 1000°C or even 1020°C in the future [6,7].
Since market demand for these alloys is still relatively low, the relevant furnace systems should ideally cover the standard annealing range as well, i.e., they should have the capability to deliver high throughputs at up to 850°C. This is all the more true in view of upstream and downstream in-line surface treatment steps, i.e., degreasing, pickling and brushing. On a dedicated system used exclusively for high annealing temperatures, an extra investment would be required to provide for these functions, apart from the cost of coiling equipment and looping towers to ensure continuous operation and to minimize scrap lengths.

Across all furnace types, conveyance of the strip without physical contact is imperative in order to meet surface quality standards.

Below we shall compare some currently available furnace designs for annealing temperatures up to 1000°C (or even 1050°C) that also deliver the customary high outputs in standard annealing regimes in the 600°C to 800°C range. The tension load acting on the strip during the annealing treatment is a key factor here.

In order to ensure the required low strip tension levels throughout the annealing process, one needs to compare the tensile stresses associated with the various equipment configurations.

**Horizontal strip flotation furnace**

For purposes of this comparison, the horizontal strip flotation furnace shall form the reference standard. In a furnace of this type, the weight force of the strip is supported by the flotation system. It acts in a direction perpendicular to the strip pulling direction, i.e., the tension resulting from the strip weight is zero. However, in order to feed and guide the strip, a specific strip pull of $\sigma = 1 - 2 \text{ N/mm}^2$ (tension related to the strip cross section) is commonly applied.

**High-convection vertical furnace**

In a vertical furnace the strip is suspended with its full weight from a roller. The resulting tension is a function of its free-hanging length. The maximum tension prevails at the topmost point where the cold strip enters the furnace.

![Fig. 1: OTTO JUNKER high-convection vertical furnace](image-url)
Weight force $F$ of the strip:

$$F = m \cdot g = \rho \cdot B \cdot d \cdot L \cdot g$$

$m$: mass; $g$: acceleration of the earth’s gravity; $\rho$: density; $B$, $d$, $L$: strip width, thickness, length

Since the strip cross section cancels out in the equation if the latter is solved for the tension, the specific strip tension (pull) $\sigma$ is independent of the strip thickness and width, i.e., it depends only on the unsupported strip length:

$$\sigma = \frac{F}{B \cdot d} = \rho \cdot L \cdot g$$

Table 1 shows the specific strip tension as a function of the unsupported strip length for typical annealing system lengths:

<table>
<thead>
<tr>
<th>Unsupported strip length</th>
<th>Maximum strip tension (at furnace entry)</th>
<th>Strip tension in the middle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N/mm²</td>
<td>N/mm²</td>
</tr>
<tr>
<td>m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>1.31</td>
<td>0.66</td>
</tr>
<tr>
<td>18</td>
<td>1.58</td>
<td>0.79</td>
</tr>
<tr>
<td>21</td>
<td>1.84</td>
<td>0.92</td>
</tr>
<tr>
<td>24</td>
<td>2.10</td>
<td>1.05</td>
</tr>
<tr>
<td>27</td>
<td>2.36</td>
<td>1.18</td>
</tr>
<tr>
<td>30</td>
<td>2.63</td>
<td>1.31</td>
</tr>
</tbody>
</table>

Table 1: Specific strip tension $\sigma$ with copper strip ($\rho= 8.920 \text{ kg/m}^3$).

In a high-performance system comprising a 15-m-long heating section and a 9-m-long cooling section, i.e., having a total length of 24 m, a maximum strip tension of 2.1 N/mm² prevails at the highest point in the case of copper strip. In the region of the maximum attainable final strip temperature, the strip tension is equal to approx. 1.0 N/mm².

OTTO JUNKER vertical furnaces are equipped with a high convection system that delivers the same heat transfer performance as a horizontal strip flotation furnace. The furnace is of modular design at the zone level, i.e., each zone has its own recirculation, heating and temperature control system. Unlike radiant heated vertical furnaces e.g. of the muffle type used for annealing steel strip [8], the high convection principle uses only a small temperature head. Thus, even in the case of a strip stoppage, there will be no excessive overheating that would inevitably result in strip breakage.
**Continuous catenary type furnace**

For a catenary type furnace, the strip tension depends on the geometry of the catenary. According to [9], the catenary curve is determined by the function

\[
y = y_0 + a \cosh \left( \frac{x - x_0}{a} \right)
\]

where the equation parameters \(y_0\), \(x_0\), and \(a\) depend on the support points (position of the deflection rollers) and on the strip length (sag).

![Diagram 1: Catenary example](image)

**Diagram 1: Catenary example**

Distance between support rollers: 21m; strip length \(L = 21.3m\); sag: 1.5m
Equation parameters: \(y_0 = -38.5m\); \(x_0 = 10.5m\); \(a = 37m\)

The horizontal force component is the same at all points of the catenary. According to [9], it can be determined from the specific load

\[
q = \frac{(m \cdot g)}{L} = \frac{\rho \cdot B \cdot d \cdot L \cdot g}{L}
\]

so that we obtain

\[
F_H = a \cdot q = \text{const.}
\]

Consequently, the horizontal component of the specific strip tension \(\sigma_h\) at any point of the catenary can be written thus:

\[
\sigma_h = \frac{F_H}{B \cdot d} = a \cdot \rho \cdot g
\]

This horizontal strip tension is present by way of total tension at the lowest sag point and constitutes the minimum strip tension throughout the entire system. In the ascending strip towards the deflection rollers the tension increases. The vertical strip tension component can be obtained from the rise of the catenary via this expression:

\[
\sigma_v = \sigma_h \cdot \tan(\alpha) = \sigma_h \cdot y'(x)
\]

\(\alpha\): Gradient angle of the catenary \(f(x)\) at point \(x\); \(y'(x)\): 1st derivative of the catenary \(y(x)\)

The maximum tension prevails at the deflection rollers. The strip tension at individual points \(x\) can be calculated by vector addition as follows:

\[
\sigma(x) = \sqrt{\sigma_h^2 + \sigma_v^2} = \sqrt{\sigma_h^2 + [\sigma_h \cdot y'(x)]^2}
\]
Diagram 2: Strip tension for the catenary from Diagram 1, material: copper ($\rho = 8,920$ kg/m³).
For reference, the strip tension in a vertical furnace also measuring 21.3 m in length is plotted underneath.

Given the horizontal force component, we can state the rule – by analogy to, e.g., overland high-voltage lines – that the less sag, the higher will be the tensile force present in the strip. The horizontal force component prevailing as minimum tension at the deepest point of sag quickly attains values that are clearly in excess of the mere weight load.

Table 2 shows the specific strip tension for typical furnace lengths:

<table>
<thead>
<tr>
<th>Distance between support points</th>
<th>Sag</th>
<th>Strip length</th>
<th>Horizontal tension = minimum strip tension (lowest sag point)</th>
<th>Maximum strip tension (at deflection rollers)</th>
</tr>
</thead>
<tbody>
<tr>
<td>m m m</td>
<td>m</td>
<td>m</td>
<td>N/mm²</td>
<td>N/mm²</td>
</tr>
<tr>
<td>15 0.5 15.05</td>
<td>4.9</td>
<td>5.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 1.0 15.18</td>
<td>2.5</td>
<td>2.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 1.5 15.39</td>
<td>1.7</td>
<td>2.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21 0.5 21.03</td>
<td>9.6</td>
<td>9.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21 1.0 21.13</td>
<td>4.8</td>
<td>5.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21 1.5 21.28</td>
<td>3.2</td>
<td>3.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21 2.0 21.50</td>
<td>2.5</td>
<td>3.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>27 0.5 27.02</td>
<td>15.9</td>
<td>16.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>27 1.0 27.10</td>
<td>7.9</td>
<td>8.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>27 1.5 27.22</td>
<td>5.3</td>
<td>5.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>27 2.0 27.39</td>
<td>4.0</td>
<td>4.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Strip tension for typical catenaries
In order to compensate to some extent for the strip tension issue inherent in catenary type furnaces, engineers often favour the remedy of installing an additional support roller still within the cooling section [2]. This device reduces the catenary length by approx. 3 m but gives rise, in practice, to significant challenges relating to, e.g., the strip-to-roller contact temperature, maintenance in the protective atmosphere (gas-tight) plant section, need for a powered roller due to small angle of wrap, interference with strip threading and passage of strip joints, etc.

![Fig. 2: Catenary type furnace with support roller – schematic sketch](image)

**Strip tension comparison**

Diagram 3 illustrates the comparison of a 21 m catenary type furnace with 1.5 m of sag to a 21 m vertical furnace. Note that the strip reaches the critical high temperatures in the middle of the line only; for clarity’s sake, the strip temperature curve is also shown.

![Diagram 3: Comparison between catenary type and vertical furnace](image)

Despite the fairly large sag (1.5 m) in this example, which makes for unwieldiness of the furnace and product, the strip tension exceeds 3.2 N/mm² over the entire length. By comparison, the strip in the vertical furnace must only withstand tensions up to 1.9 N/mm², and in the region of the high strip temperature the tension will not even reach 1.2 N/mm²; this is very important particularly with annealing temperatures over 850°C.
Cooling

Commonly the strip is cooled by recirculation cooling in a protective gas atmosphere, followed by immersion cooling in water. The water cooling step in the so-called water seal box provides the option of highly effective aftercooling to temperatures significantly below 70°C while also perfectly sealing off the protective gas-filled furnace chamber towards the ambient atmosphere at the exit end. As a result, the water seal is typically employed on all three variants.

In both catenary type and horizontal strip flotation furnaces it should be noted that the strip, upon exiting the air/gas cooling section, comes into contact with a deflection roller before dipping into the water. In order to prevent burning of the rubber coating on the deflection roller, the strip must get cooled down in the air/gas cooling section at least to this roller’s maximum service temperature. It follows that the air/gas cooling section must be sufficiently long on catenary type and horizontal strip flotation furnaces.

In the vertical furnace the strip enters the water directly, without any physical contact. Accordingly, the temperature may be somewhat higher here and the air/gas cooling section can be made shorter. On catenary type and strip flotation furnaces, this leads to a typical furnace-to-cooling section length ratio of approx. 4:3, whereas a vertical furnace plant may, for this reason, do without a cooling section altogether.

Thus, the cooling section of a vertical furnace will normally be several meters shorter for the same annealing output. As a result, equipment height is reduced and the already lower strip tension is further diminished.

To prevent the furnace atmosphere from becoming enriched with steam, all current OTTO JUNKER furnaces have an OTTO JUNKER steam extraction system with condensate separation fitted in the area of transition to the water-seal, in addition to water jet cooling at the immersion point.

In both horizontal strip flotation and catenary type furnaces, the deflection roller at the point of immersion into the water-seal is usually an idling roller. All idling rollers require a strip tension of 1-2 N/mm² to be imparted movement. In the vertical furnace, this last-mentioned deflection roller is absent altogether. The underwater roller is usually a live roller on OTTO JUNKER systems, regardless of furnace type, so that the additional strip tension required to drive it is eliminated.
**Strip tension control**

The strip tension and strip speed in a vertical furnace or horizontal strip flotation furnace is controlled via the strip pulling system. This is achieved via standard load cells and/or so-called dancer rolls.

For the catenary type furnace to attain the same performance level as the reference systems, it is equipped with a high convection nozzle array which must be arranged along the catenary line of the strip. To prevent the strip from colliding with the nozzles, a sag control system using a sag sensor in the furnace and cooling sections is employed. Fitted in an enclosure, this device must resist the prevailing ambient conditions (temperature and forming gas atmosphere) and would not be readily accessible for maintenance. Alternatively, a safe and reliable measurement from outside the chamber – e.g., „remotely“ through a sight glass – would have to be ensured. As the strip still exhibits its „as-rolled“ hardness upon entering the furnace, care must be taken to make it follow the intended catenary curve so as to avoid collisions with the high convection nozzles.

In the event of strip breakage it is difficult to imagine that, without access to each individual zone (to be cooled down), the strip could be rethreaded from outside by means of a winch in the manner known from strip flotation furnaces and vertical furnaces.

**Space requirements**

In terms of space-use efficiency, the horizontal strip flotation furnace takes first place. It is of relatively flat design and can be easily installed on a second deck – i.e., a steel platform – above the strip handling equipment, even in a production area of normal ceiling height.

A vertical furnace will not usually fit into a standard-height industrial building. At least part of the production area will typically have a raised ceiling section which then also accommodates one of the strip looping towers, eliminating the need for large pits [10].

The catenary type furnace constitutes an intermediate solution. When fitted in a building with standard ceiling height occupying the full vertical space (i.e., installation on two decks is impossible, as distinct from the horizontal strip flotation furnace), its output capacity is very limited if strip tension levels of, e.g., 2 N/mm² must not be exceeded at the most critical (hot) point.
Conclusion
Horizontal strip flotation furnaces are still the ideal solution and the technology of first choice when it comes to annealing of copper and copper-alloy strip. However, at annealing temperatures of 850 - 900°C, they reach their limit of performance and, specifically, load bearing capacity with the engineering materials available today. New copper alloys tend to require annealing at temperatures up to 1000°C. The catenary type furnace supports such annealing regimes but only at the cost of major compromises. Compared to a vertical furnace, it is of relatively low height and requires no tall ceilings, but on the downside it is subject to restrictions in length (= throughput capacity) and presents some complexities at the level of maintenance and process stability. Where enough vertical space is available, the high convection vertical furnace with its substantially reduced strip tension constitutes the no-compromise solution. Due to the lower tensional stresses, it is also possible to design larger systems with a higher output.

OTTO JUNKER - partner to the copper semi-finished products industry for over 90 years - will be glad to provide advice and to recommend the most suitable solution from a broad product range. In addition to strip flotation and catenary type furnaces, the portfolio also comprises high-convection vertical furnaces. In the vertical furnace category alone, three systems sourced from other manufacturers were converted to OTTO JUNKER's high-convection technology in recent years.

Fig. 4 – Conversion of a vertical furnace by OTTO JUNKER in 2016
References


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Company Profile
Established in 1924, OTTO JUNKER GmbH draws on more than 90 years of experience and continuous product development. The company is represented by subsidiaries, service agencies and sales offices all over the world. The product range embraces melting, casting, heating and heat treating equipment for the aluminium and copper industries as well as melting and casting equipment for iron and steel foundries.

Our foundry in Lammersdorf produces high-grade sand castings from iron, nickel and cobalt-based materials, both as cast and fully finished. In the attached machining section, precision parts are made for demanding applications.

GießereiAlternativ-Text fürKurzeTextabschnittemitwenig Zeichen:Beyond that, the in-house special-steel foundry in Lammersdorf produces finish-machined castings ready for installation.

Since 1982, the company has been owned by the OTTO JUNKER FOUNDATION. Consistent with the Foundation’s charter, it promotes the training of young engineers at the RWTH Aachen and sponsors research and development in the fields of metallurgy and electrical engineering.