CO_2-Reduction by Energy-Efficient Vacuum Heat Treatment Processes and Plants

Dr. Klaus Loeser[1] and Gunther Schmitt[1]

[1]*ALD Vacuum Technologies GmbH, Otto-von-Guericke-Platz 1, 63457 Hanau, Germany*

One measure to achieve the demanding future climate targets with regard to CO_2 reduction is to reduce the energy consumption of thermal process plants. In the field of case hardening of transmission components, low-pressure carburizing systems with high-pressure gas quenching are often used in the automotive and supplier industries. The main energy source of this technology is electrical energy, as the equipment is heated electrically without exception. The paper presents various measures for reducing the consumption of electrical energy during the heating and carburizing phase as well as during the quenching phase by means of improved process control and optimization of the plant technology. The paper compares the effect of different measures in the area of process, plant and fixture material and quantifies the impact on electrical energy consumption and thus the CO_2 footprint.

Keywords: *CO_2-Reduction, Energy efficiency, Low-Pressure Carburizing, High-Pressure Gasquenching, High-Temperature Carburizing*

1. Introduction

In Germany, over 50% of the total end energy consumption (2.500 TWh in 2019) is converted into heat energy (1.392 TWh). Approximately 60% of this generated heat serves the purpose of heating buildings and producing warm water, among other uses. The remaining 40% of the produced heat finds its application in providing process heat within various industries. Consequently, process heat plays a significant role, contributing around 22% to the overall energy consumption in the country (541 TWh). Therefore, one measure to achieve the demanding future climate targets with regard to CO_2 reduction is to reduce the energy consumption of thermal process plants.

In the field of case hardening of transmission components, low-pressure carburizing systems with high-pressure gas quenching are often used in the automotive and supplier industries. The main energy source of this technology is electrical energy, as the equipment is heated electrically without exception. As a consequence, the reduction of the electrical energy consumption is the major step to achieve the demanding future climate targets.

2. Measures to reduce energy consumption

2.1 Energy fluxes in a vacuum furnace process

Electrical energy fluxes in LPC-processes with high pressure gas quenching can be demonstrated in a Sankey-Diagram.

Figure 1 shows two typical production examples e.g. massive parts like gear shafts or light parts like internal gears.

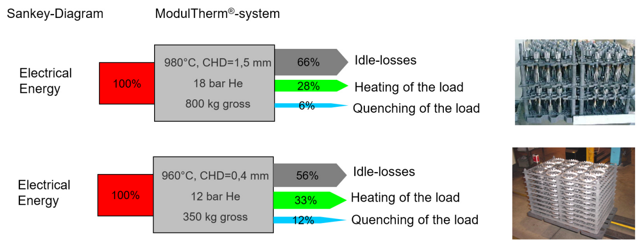

Figure 1. Energy fluxes in vacuum furnace processes

It is shown that the idle heat losses dominate the energy losses while the energy consumption during quenching is low, relative to the total consumption. The higher the case hardening depth (CHD) and the corresponding total process time the more important are the idle heat losses.

2.2 Multi-chamber versus continuous furnaces

In the context of system ramp-up or production expansion, varying process capacities come into play (Figure 2). Continuous systems, for instance, are typically set up to accommodate the ultimate and maximum production scale. However, this approach often entails a downside - a surplus of production capacity is initiated right from the start, resulting in unnecessary energy wastage and additional costs.

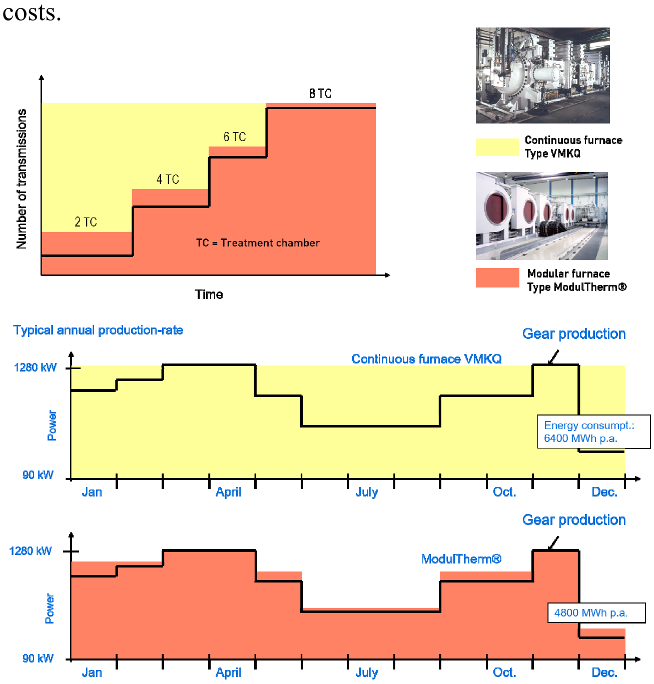

Figure 2. Energy consumption of continuous versus modular furnaces

A more efficient alternative lies in the realm of modular systems, wherein production sizes can be tailored to align with the current production requirements. This approach not only curbs energy wastage but also facilitates energy conservation by avoiding the operation of excess production capacity that isn't immediately needed.

2.3 Optimization of furnace insulation

Figure 3 illustrates the relative idle heat loss experienced by a treatment chamber operating at 950°C and under a 5mbar Nitrogen atmosphere. The values presented specifically pertain to insulation losses, excluding structural factors such as power feed-throughs, load support, etc.

Traditionally, the first-generation single-vacuum-chamber furnaces used a single layer graphite rigid felt as the primary insulation material, which serves as the baseline at 100% heat loss. In an effort to mitigate heat losses, an innovative approach was adopted - the incorporation of ceramic fibre modules as back-insulation. This intervention resulted in a substantial reduction in heat losses compared to the standard. Furthermore, the effectiveness of heat loss reduction was heightened by increasing the thickness of the ceramic fibre modules, leading to a notable 39% decrease in heat losses. Looking ahead, the potential for even greater heat loss reduction lies in the adoption of microporous insulation materials, offering the promise of a 55% reduction in losses as compared to the standard.

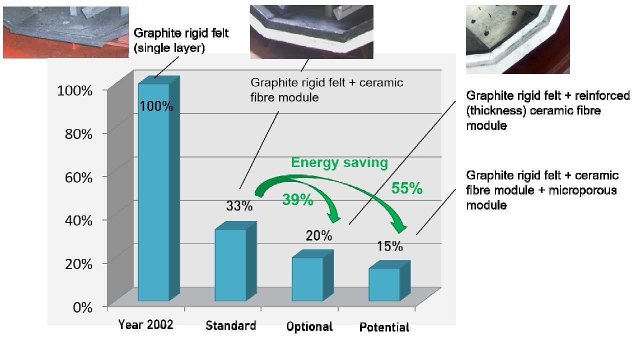

Figure 3. Optimization of furnace insulation

However, it's important to acknowledge that when engineering treatment chamber insulation, additional consequences must be considered. This includes the possible emergence of an undesirable Cristobalit-phase in the ceramic insulation if temperatures surpass 900°C, as well as a certain compromise in temperature flexibility, such as during transitions from carburizing to hardening temperatures.

2.4 High-temperature carburizing

Let's consider an illustrative example that highlights the impact of high-temperature carburizing (HTC) on energy consumption during low-pressure carburizing (LPC). For this demonstration, we'll focus on a specific LPC scenario: treating gear parts with a gross weight of 800 kg, carburized to a case depth (CD) of 1.5 mm (Figure 4). The carburizing process occurs at 930°C (standard) and at 1030°C (HTC), with subsequent quenching using 12 bar He in both instances. When we plot the energy consumption per kilogram of load, distinct trends emerge. Notably, the energy required for heating is higher in the HTC process due to the elevated temperature used. The energy needed for quenching remains consistent. However, a significant contrast arises in terms of energy consumption attributed to idle losses during carburizing and diffusion. In the case of the HTC process, these losses are substantially diminished. Paradoxically, despite the higher specific idle losses associated with the heightened process temperature, this is overshadowed by the effect of the shorter carburizing and diffusion phases characteristic of HTC.

Summing up the results, the HTC approach yields an energy saving of 21% in this example. This underscores the considerable potential of high-temperature carburizing not only in influencing energy consumption but also in optimizing overall process efficiency.

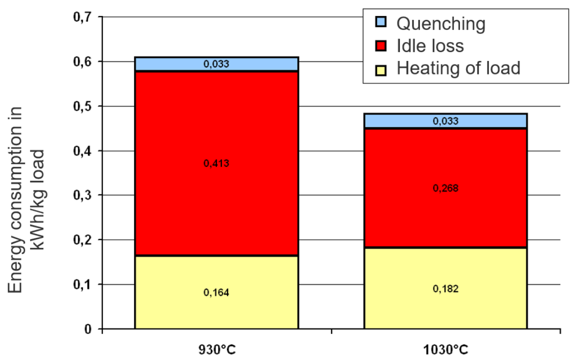

Figure 4. High-temperature carburizing

To harness the benefits of High Temperature Carburizing (HTC) while circumventing the risk of unwanted grain growth, the steel industry undertook the task of designing novel steel grades engineered to exhibit robust grain stability. The primary objective was to create micro-alloyed steels with the inherent capacity to withstand the high carburizing temperatures reaching up to 1050°C, associated with the potential for detrimental grain growth.

In response to this challenge, steel manufacturers succeeded in developing suitable steel grades. Testing validated the efficiency of these new alloys in meeting the grain stability criteria. However, despite these achievements, HTC still does not experience a brake through or widespread industrial implementation.

Several potential factors contribute to this outcome. Achieving grain stability proves to be a complex endeavor. It is evident that ensuring grain stability extended beyond the mere addition of appropriate microalloying elements. Rather, it necessitates meticulous control of the entire steel manufacturing process.

Furthermore, the adoption of the newly formulated steel grades faces a practical hurdle. Only a select few steel suppliers possess the capability to deliver these specialized alloys. This scarcity leads to higher costs and reduces competitive options for potential users.

Some customers found a workaround by resorting to HTC using conventional, standard steel grades. This was achieved through the application of single-hardening processes, allowing them to tap into the benefits of HTC without necessitating the use of the newly developed alloys.

As an example, Figure 5 highlights the correlation between the effective case hardening depth and the total treatment time, comparing various processes.

The standard carburizing process (blue line) entails carburizing at 950°C followed by direct oil quenching within a sealed-quench furnace. The blue line represents the total treatment time corresponding to this method. The high temperature carburizing (HTC) process (red line) involves carburizing at 1050°C within an LPC-system, with subsequent direct high-pressure gas-quenching. Although this approach reduces process time significantly, it leads to grain growth in standard case-hardening steel quality. The HTC process with single hardening (green line) is characterized by carburizing at 1050°C in an LPC-system, followed by a gas cooling, reheating to austenitizing temperature and a high-pressure gas-quenching. This strategy achieves a reduction in process time and successfully avoids grain growth.

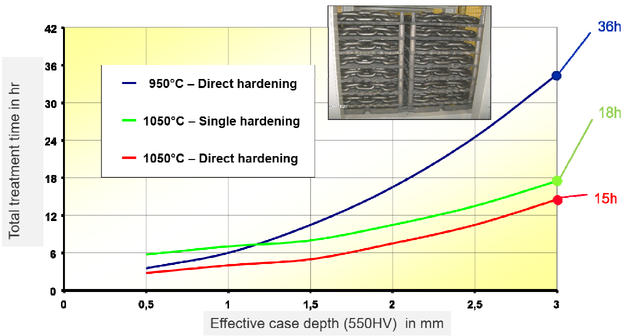

Figure 5. High-Temperature Carburizing (Single hardening)

The process times presented in Figure 5 are relevant to an effective case depth (ECD) of 3mm. It's noteworthy that a remarkable 50% reduction in total process time is achievable through these approaches, thereby offering an energy-saving potential of approximately 25%.

It's important to note that this process might not be suitable for carburizing processes involving shallow case depths. In the provided example, the transition point where single hardening becomes advantageous is approximately at 1.2 mm ECD. This observation underscores the importance of tailoring the treatment approach to specific case depth requirements, optimizing efficiency while maintaining desired material properties.

2.5 Fixturing

Reducing the weight of fixtures in industrial processes is an effective measure to minimize energy consumption. This is especially notable in the case of replacing alloy fixtures with carbon-fibre reinforced carbon (CFC) fixtures in technologies such as low-pressure carburizing and high-pressure gas-quenching.

CFC fixtures are much lighter than alloy fixtures due to the lower density of carbon-fibre reinforced carbon. This reduction in weight not only contributes to energy savings but also enhances operational efficiency and ease of handling. As shown in Figure 6, the energy needed to heat up the load to a specific temperature of 1000°C is reduced by an impressive 79% as compared to the use of alloy fixtures.

Data: GTD Graphit Technologie GmbH

Material	CFC	Cast Alloy (1.4818)
Density	1,6 kg/dm^3	7,9 kg/dm^3
Weight Fixture	1 kg	12 kg
Spec. Heat Capacity	1,8 kJ/kgK	0,7 kJ/kgK
Energy requirement for heating to 1000°C	1.764 kJ (21%)	8.232 kJ (100%)
Bending strength at 1000°C	~ 230 MPa	~ 10 MPa
Thermal expansion coefficient	5×10^{-6} K^{-1}	12×10^{-6} K^{-1}

Figure 6. Comparison of CFC fixtures with alloy fixtures

The higher strength of CFC fixtures results in less deformation of the fixture during the heating and processing phases. This characteristic of CFC fixtures can play a crucial role in reducing distortion of the parts being processed, thus improving the overall quality of the final products.

Although the initial investment in CFC fixtures might be higher, the long-term energy cost savings, improved process efficiency, and reduced part distortion can result in significant cost savings over the life cycle of the fixtures.

3. Summary

One measure to achieve the demanding future climate targets with regard to CO_2 reduction is to reduce the energy consumption of thermal process plants. In the field of case hardening of transmission components, low-pressure carburizing systems with high-pressure gas quenching are often used in the automotive and supplier industries. The main energy source of this technology is electrical energy, as the equipment is heated electrically without exception.

It has been shown in the paper that a major part of the energy losses are idle losses during heating, carburizing and diffusion at high temperatures. As a result, the energy consumption can be significantly reduced by improving the thermal insulation of the furnace.

By using high-temperature carburizing, process time can be reduced significantly resulting in energy savings. It is shown that despite the higher specific idle losses associated with the heightened process temperature, this is overshadowed by the effect of the shorter carburizing and diffusion phases characteristic of HTC. However, attention is needed as standard case hardening steels tend to unwanted grain growth at these temperatures.

To make use of HTC with standard case hardening steels, single hardening processes may be used resulting in significant energy savings. However, the effect is dependent on the total case hardening depth.

The use of carbon-fibre reinforced carbon (CFC) fixtures instead of alloy fixtures leads to a tremendous reduction in fixture weight resulting in energy savings during the heating and cooling process. Moreover, they exhibit excellent high-temperature strength, reducing deformation of the fixtures. This leads to minimized distortion of the parts during heating and quenching which in turn avoid subsequent energy consuming hard machining processes.