Low Pressure Carburizing with High Pressure Gas Quenching

Herwig Altena and Franz Schrank

Low pressure carburizing offers, on account of technological advancements, an alternative to conventional gas carburization of gear parts for the automotive industry. The requirement of reduced grinding operations and costs causes demands for reduced distortion and carburization without surface oxidation, which can only be fulfilled by means of vacuum technology.

A low pressure carburizing (LPC) method is presented that is distinguished by a high mass flow density of carbon at the beginning of the process. Along with a higher carburization temperature, cycle times can be reduced significantly. The incorporation of low pressure carburizing systems in production lines is an attractive proposition, in particular when used in connection with high pressure gas quenching, which produces bright, oil-free surfaces.

With regards to high pressure gas quenching, the most stringent requirements on environmental protection are met. Furthermore the distortion of critical parts may be reduced in many applications.

The principles of the process technology and their applications will be discussed. Furthermore a new continuous LPC system with high pressure gas quenching will be presented. The system allows a throughput capacity of more than 700 kg/hr. gross weight. The design of the quenching chamber was optimized by means of finite element simulation of the gas flow pattern, leading to an enhanced quenching rate and to improved core hardness of heavy gear parts.

Management Summary

High demands for cost-effectiveness and improved product quality can be achieved via a new low pressure carburizing process with high pressure gas quenching. Up to 50% of the heat treatment time can be saved. Furthermore, the distortion of the gear parts could be reduced because of gas quenching, and grinding costs could be saved. This article gives an overview of the principles of the process technology and the required furnace technology. Also, some examples of practical applications are presented.

Introduction

Conventional gas carburization already has a firm place as a thermochemical treatment process; carburization has become virtually indispensable in many industrial sectors, in particular in the car industry. Thanks to further development in the field of technology, gas carburization has reached a stage that guarantees good reproduction of results when appropriate checks and maintenance are carried out. However, this process is bound by certain limits, in particular where environmentally friendly methods and an oxide-free surface are required.

Recent years have seen a remarkable increase of interest shown in carburization using vacuum systems. Low pressure carburization has undergone major developments compared with its initial position around 20 years ago, and it has now achieved industrial maturity. Numerous older papers deal with low pressure carburizing (Refs. 1–4), at a pressure range between 200 and 500 millibars by the use of methane as carburizing gas. Due to a complete change of process parameters and carburizing gas, we are now able to present a reproducible and consistent process with very uniform results.

The advantages of low pressure carburization over gas carburization are not only the creation of a surface entirely free of oxide and the method's environmental friendliness, but also an improvement in deformation behavior achieved by combining carburization with gas quenching, a reduction in batch times by increasing the carburization temperature, lower gas and energy consumption and the prevention of soot to a large extent.

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Carburizing temperature	900–1,050°C
Carburizing pressure	1–30 millibar
Carburizing gas	Propane (acetylene)
Duration of treatment	10 min.–20 hr.
Carburizing depth	0.2–3 mm

Figure 1—Process parameters.

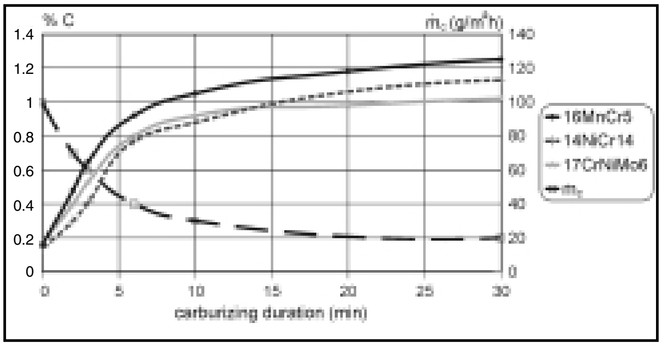

Figure 2—Surface content of carbon vs. carburizing duration.

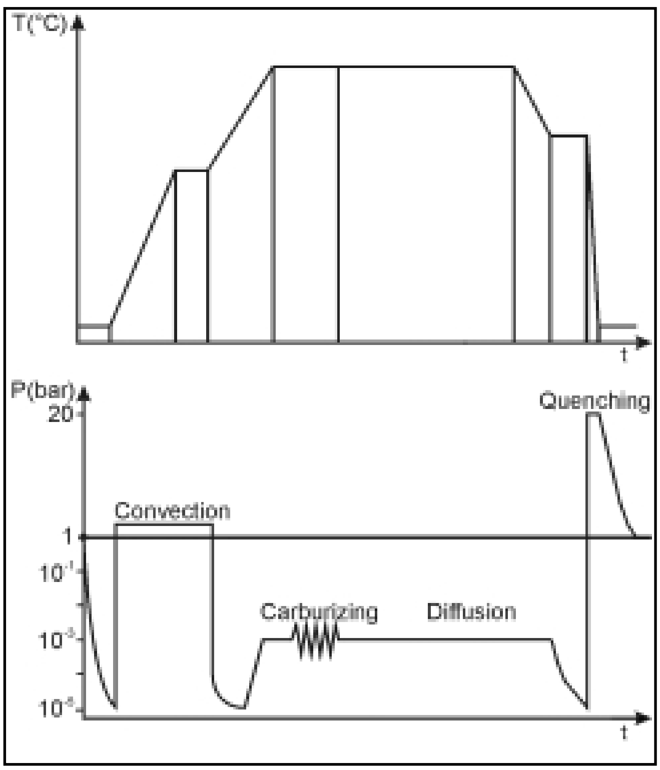

Figure 3—Process flow schematic.

10% coarse grain	18CrNi8	16MnCr5	17CrNiMo6	20MnCr5
900°C	> 8 hr.	> 8 hr.	> 8 hr.	> 8 hr.
940°C	4 hr.	> 8 hr.	> 8 hr.	> 8 hr.
980°C	1 hr.	4 hr.	4–8 hr.	> 8 hr.
1,020°C	5 min.	5 min.	15 min.	15 min.

Figure 4—Grain growth vs. carburizing temperature and duration (after V. Schüler, Ref. 7).

Mass Transfer and Reaction Mechanism

The process parameters for low pressure carburization are summarized in Figure 1. In general, the pressure range used is less than 30 millibars with sequences of pressure changing (gas inlet with intermediate evacuating). These sequences of pressure changes allow a much better uniformity of carburization in drilled holes as well as blind holes, due to the fact that the transfer of fresh reaction gas is much easier.

Propane is used in general as process gas in low pressure carburizing. In contrast to gas carburization, no oxygen-containing reaction gases are used in vacuum systems, and therefore carbon potential control cannot be carried out in low pressure carburizing. The most important parameter in this case is the carbon mass flow density (m_c), which is defined as the quantity of carbon introduced into the material per unit of surface and time. This parameter allows a direct comparison with gas carburization (Ref. 5).

The reaction ratio of the propane thermal decomposition, which proceeds favorably on the hot surface of the charge, has been determined in a single chamber furnace with an average load (surface of the charge, approximately 2.5 m^2) and 3 millibar gas pressure. The results proved a better reaction ratio with rising carburizing temperature and a decreasing amount of propane, which can be explained by the longer stay in the furnace. In total, 40–60% of the theoretically available carbon was deposited (Ref. 6).

In addition to methane, there arise ethylene and acetylene as intermediate products of the decomposition reaction, which are responsible for the carburizing reaction and can be used as process gases as well. The uniformity in carburizing of long blind holes and transitory drilled holes can be improved by using acetylene. Methane at all examined temperatures cracked less than 3% and is not relevant for low pressure carburizing when working in millibar range. To achieve sufficient methane thermal decomposition, the CH_4 partial pressure must be increased to more than 300 millibar. At more than 300 millibar, soot could develop in the LPC system.

To minimize the carburizing time, the process allows a high carbon mass flow of m_c = 100 (–200) g/m²hr. Therefore, in only a few minutes, a surface carbon content of more than 1% is achievable (see Fig. 2). Also, a dynamic balance between the carbon supply and the diffusion speed into the basic material can be created by reducing the carbon mass flow. This reduction can be achieved by reducing the amount of the process gas flow during carburizing.

Figure 3 shows a typical process procedure in a single chamber vacuum furnace with the process steps: heating up, low pressure carburizing (pulsed), diffusion, reducing to hardening temperature and gas quenching. The carburizing can be simulated by a diffusion calculation program. Practical test results have been used to confirm the accuracy of simulation programs and as input to revise the simulation and refine the process parameters.

By modifying the carburizing time and the diffusion time, the necessary surface carbon content and hardening depth can be adjusted.

Diffusion

By implementing vacuum technology, the increase of carburizing temperature can be applied without any limitations caused by the furnace. (In contrast, atmospheric furnaces usually have a maximum temperature of 950°C for continuous systems and chamber furnaces a maximum temperature of 1,000°C.) However an increase in carburization temperature may not be possible depending on steel quality and other metallurgical factors.

Detailed tests performed by V. Schüler (Ref. 7) on standard fine-grain stabilized rods have shown that if the aluminum and nitrogen levels of the steels are sufficiently high, a carburization temperature of 980°C at a holding time of 4–8 hours will not lead to grain coarsening. The maximum admissible share of grain coarsening is limited to 10% (see Fig. 4). This gives the possibility of achieving effective hardening depths of 1.4–2 mm by direct hardening without intermediate isothermal annealing.

If the carburizing temperature is increased to 1,020°C, the maximum holding time is then limited to 15 minutes, which does not seem sensible (hardening depths of ~0.45 mm). Isothermal annealing followed by austenitizing leads to an extension of the process time, which can only be compensated at carburizing depths of more than 1.4 mm and temperatures of 1,020°C.

Quenching

The quenching is achieved with 10–20 bar nitrogen or helium, depending on the use of the materials, the maximum wall thickness of the workpieces, their geometry, the desired case and core hardness and the design of the furnace (single chamber or multichamber furnaces; see the next section: **Design of Systems**)

Substituting oil quenching with high pressure gas quenching guarantees not only a better surface quality, but also—in general—an improvement of the distortion. In addition, gas quenching spares one cleaning process as well as post-finishing costs, due to a reduction of the grinding allowances (Ref. 8). The demand for oxide-free carburizing only makes sense in combination with minimized distortion. By saving on post-finishing costs, one cleaning process and reduced disposal costs, low pressure carburizing represents an economical alternative to conventional gas carburizing.

Design of Systems

Low pressure carburization in general can be commonly realized in conventional single chamber vacuum furnaces, which can be adapted with gas distribution equipment for the process gas, special graphite insulators for the electrical power supply of the heating and some further technical adaptations. For achieving sufficient quenching speed in a single chamber furnace, the use of pressures up to 20 bar and helium or hydrogen as quenching gas is recommended.

The preferred furnace technology allows 10–20 bar N_2 quenching with a cold quenching chamber, achieving sufficient quenching rates for a great deal of different workpieces and materials. The transport of the charge between the two chambers is executed according to the well proven roller hearth principle, allowing quick transportation of the charges with a minimum of vibration (Fig. 5).

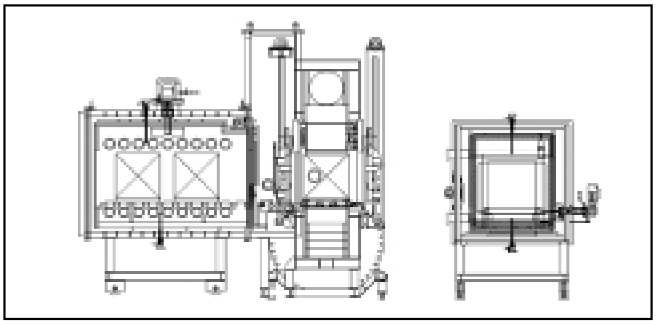

Figure 5—Schematic for two-chamber vacuum furnace.

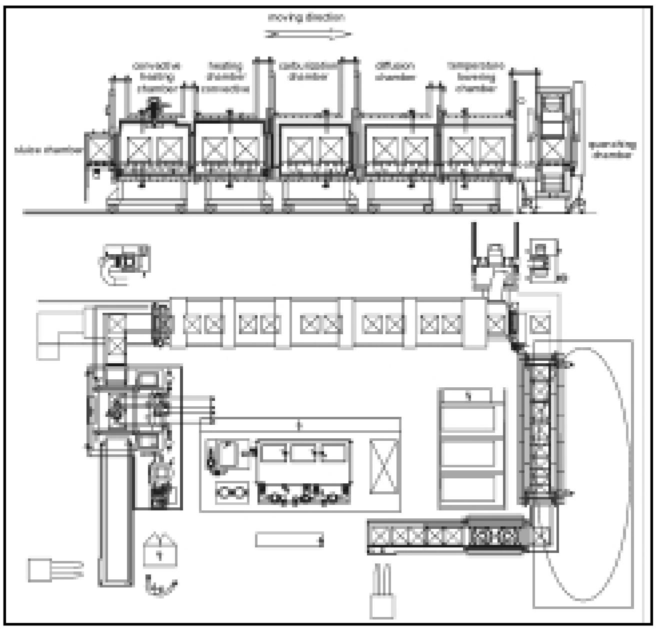

Figure 6—Schematic for low-pressure carburizing system.

Figure 7—Continuous low-pressure carburizing system.

For higher capacities, as required by the car industry, continuous, multi-chamber furnaces are mainly used for low pressure carburizing. These furnaces include a sluice chamber, a heating chamber (which allows convective heating with 1–2 bar nitrogen), one to two carburizing chambers, two to three diffusion chambers (which permits decreasing to hardening temperature) and a quenching chamber (which can be used as a sluice to unload the charge after quenching). Figure 6 presents a scheme for a continuous low pressure carburizing system. Figure 7 shows an overview of the entire LPC system.

The cold quenching chamber allows efficient quenching of numerous case hardening materials of different shapes and wall thicknesses. A cooling pressure of 10–20 bar nitrogen is sufficient to achieve core hardness for gears as demanded in the car industry. For high quenching rates, helium quenching in combination with a helium recycling unit can be achieved, too.

Carburizing Results

Uniformity. The uniformity of low pressure carburizing over the complete charge proved to be the main problem in the pressure range of a few 100 millibar, as observed in thorough tests by Chatterjee-Fischer (Ref. 1).

Reducing the pressure to only a few millibar as well as sequences of pressure changing (gas inlet with intermediate, short evacuating phases) have changed the conditions totally. The uniformity of the carburizing was examined on a test charge of 300 kg (rods $30^{\varnothing}$ x 500 mm, total load with a surface of 5 m^2).

Figure 8 shows the carbon profile of five turned test samples, which have been distributed in the complete charge chamber and carburized for three hours at 930°C. The case depth at 0.35% C was in the range of 0.80–0.85 mm.

Workpiece geometry. The efficiency of the process for carburizing in drilled holes as well as blind holes was examined on a test sample ($40^{\varnothing}$ x 100 mm) and the hardness profile was measured at different positions. Under the chosen geometrical conditions, the carburizing results were very uniform in both holes (see Fig. 9). Figure 10 shows etched microsections of workpieces (pistons and nozzles) also having a large number of drilled holes and a few blind holes. The workpieces were carburized to an effective hardness depth of 1–1.2 mm. The carburizing result for all the holes was very uniform. On the two microsection probes illustrating different geometry gears, a very high uniformity of carburizing has been achieved at the tips, flanks and roots of the teeth.

The use of acetylene leads to a further improvement of uniformity in carburizing very long blind holes and transitory drilled holes. Even critical components, such as pump noses and injection nozzles, can be treated to uniform results in spite of complex geometry and high charging density.

Application examples: gears and gear shafts. Depending on the geometry of the gear, the module and the required case depth, occasional minor deviations occurred regarding the hardness profile on the tips and bases of the teeth. Figure 11 shows a drive pinion and a ring gear made of 16MnCr5 (~SAE

5115), which have been carburized to an effective case depth of 0.6 mm at 625 HV. The uniformity of the carburizing on the tips, flanks and bases of the pinion teeth can be seen from the hardness profile in Figure 12. The surface carbon content was approximately 0.73%.

The minor differences in the hardening procedure can be referred as well to the higher carbon availability in the tooth base at low pressure carburizing, as to the minor differences in quenching velocity from the top of the tooth to the throat of the tooth.

Some other examples are shown in Figures 13 and 14 of gears and synchronized rings, which have been carburized in vacuum furnaces. Remarkable once again is the very good uniformity of carburizing of the tips and the bases of the teeth of synchronized rings and the very uniform results even at carburizing depths of only 0.3 mm (see Fig. 15). The carburizing was achieved at 930°C and the total time for carburizing and diffusion amounted to 8 minutes.

How densely gear shafts for the car industry have been loaded for low pressure carburizing is shown in Figure 16. Even with this dense load, uniform carburizing results have been achieved.

The improved quenching capacity of modern low pressure carburizing systems with a separate quenching chamber also makes possible the case hardening of solid components of truck-gear production. Numerous satisfactory treatment results of massive shafts (15–25 kg/piece) and synchronized rings (up to 6 kg/piece) extend the range of application of the process and indicate new operation areas.

Application examples: sintered materials. Sintered materials showing a residual porosity cause difficulties in gas carburizing processes due to the fact that the large surface of the pore channels allows full carburizing in very short time. On the contrary, low pressure carburizing has an advantage in that the carburizing is confined to the surface of the workpiece, if the size of the pores is a great deal less than 100 µm.

In this case, the length/diameter correlation is usually far beyond 15 and the LPC process does not allow carburizing of these very thin "blind holes" because fresh process gas does not penetrate into the pores. Furthermore, the very short processing times of LPC (just some minutes) can be controlled much better than normal gas carburizing processing of sintered parts.

Gears made of Sint D30 with a diameter of 10 mm were carburized. A case depth of 0.25 mm was required to avoid full carburizing of the teeth.

The carburizing was achieved with propane, at a pressure of 3 millibar, at 930°C and with a carburization time of 6 minutes.

To improve process security and uniformity in carburization, the process can be effective at temperatures of 850–900°C while prolonging the carburizing duration. The process control and gas absorption is adapted to the specific workpiece.

Summary

Low pressure carburizing offers, on account of technological advancements, an alternative to conventional gas carburiza-

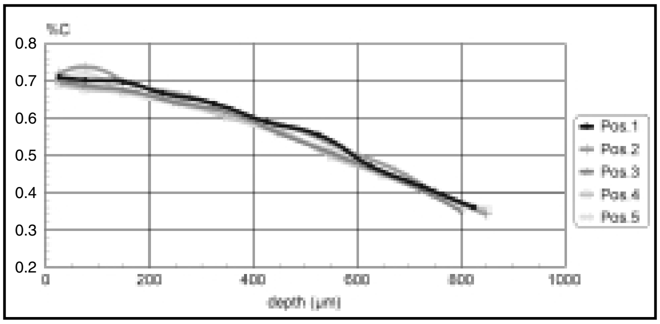

Figure 8—Carbon profile for 300 kg batch.

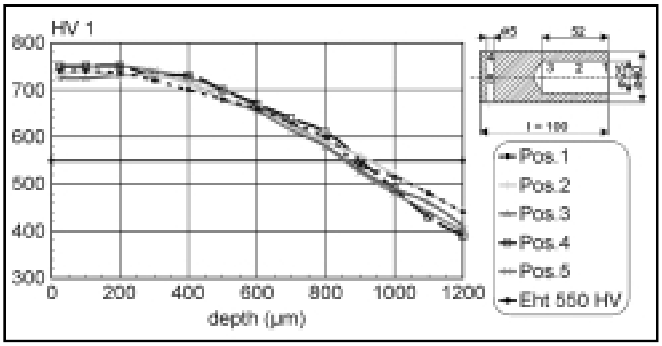

Figure 9—Hardness profile of 16NCD13 test piece.

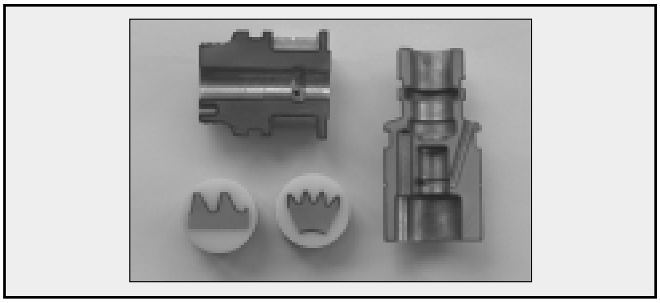

Figure 10—Micrographs.

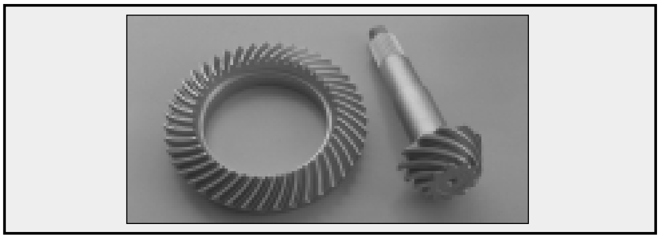

Figure 11—Ring gear and drive pinion.

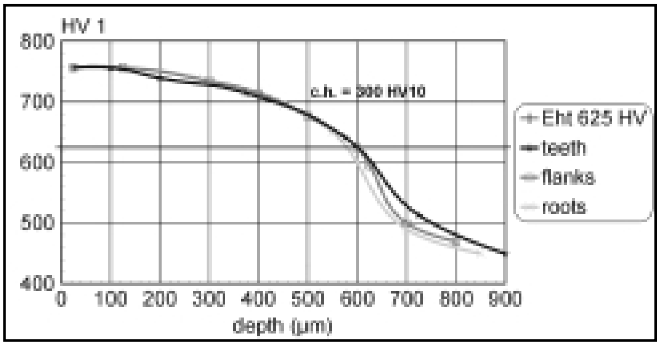

Figure 12—Hardness profile 16MnCr5 gear shaft.

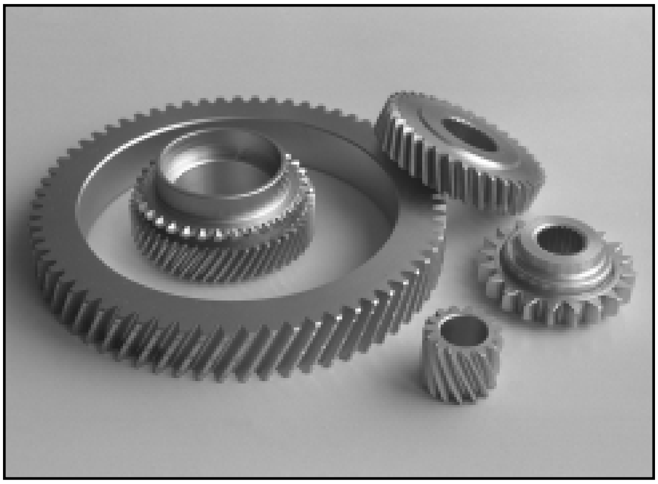

Figure 13—Various gear wheels.

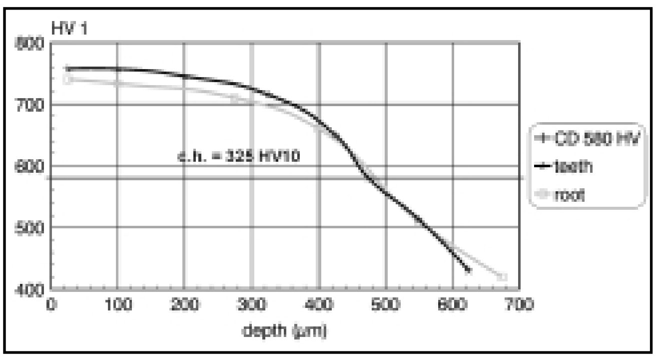

Figure 14—Hardness profile of 16MnCr5 gear wheel.

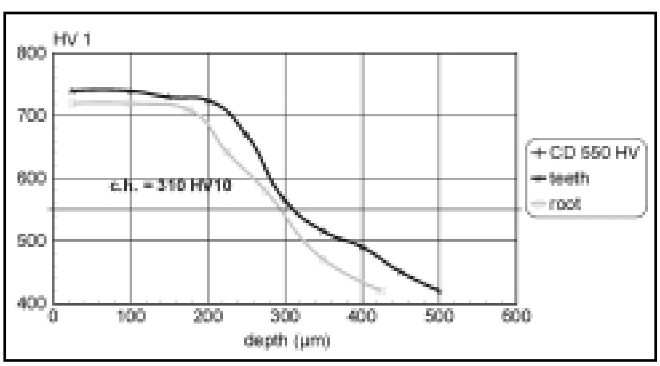

Figure 15—Hardness profile of smaller 16MnCr5 gear wheel.

Figure 16—Load density of gear shafts.

tion. Apart from the oxidation-free surface of the charge, the process distinguishes itself by a short process time, higher process temperatures and the additional possibility of using high pressure gas quenching. Problems like the formation of soot or lack of uniformity of low pressure carburizing have been eliminated by optimizing the furnace technology as well as the process parameters. A calculation program allows complete control of the carburizing process with a very good correspondence to practical results.

The incorporation of vacuum systems in production lines is an attractive proposition given the relatively short treatment times involved, in particular when used in connection with high pressure gas quenching, which produces bright, oil-free surfaces. If oil quenching is not used, it is possible to satisfy the most stringent requirements of environmental protection regulations. In addition, gas quenching frequently reduces deformation of components, which may considerably cut the costs of further processing. In this connection, the demand of carburizing without surface oxidation has a new importance, too.

Low pressure carburizing can be achieved in one chamber, but two- and multi-chamber systems are preferable. For quenching, nitrogen or helium under 10–20 bar pressure is used. For continuous systems, gas cleaning and recovery is also possible.

Higher capacities as required by the car industry can be achieved in continuous furnaces with separate chambers for heating, carburizing, diffusion and quenching. Such systems can achieve net-throughput rates of 500 to 1,000 kg/hr., depending on the carburizing temperature and the required effective hardening depth.

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