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Automated Vacuum Heat-Treat Systems in the Powertrain Industry

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Gears and gear shafts are typically subjected to the highest dynamic stresses of all powertrain components. Today comprehensive production experience is available with heat-treat systems, especially regarding high-volume, continuous production of powertrain components.[2] The following article describes the present state of this technology and relays experiences in large-batch drivetrain-component production.

In order to obtain the specified metallurgical properties on the gear tooth and the gear tooth root, powertrain components must be heat treated (Fig. 1). The overwhelming majority of these parts are currently heat treated by case hardening in atmosphere gas-carburizing furnaces and quenched using oil only. The higher quality and more demanding performance specifications for these components require improved heat-treatment methods. Therefore, new case-hardening technologies such as vacuum carburizing in combination with high-pressure gas quenching have been aggressively developed in recent years. There is tremendous interest in this type of heat-treat technology and the related furnace systems. Particular interest is directed toward the heat treatment of highly stressed gears.[1]

Vacuum Carburizing (a.k.a. Low-Pressure Carburizing or LPC)

Vacuum carburizing is performed at pressures less than 20 mbar (15 torr), and oxygen-free hydrocarbons like acetylene (C_2H_2) are used. The level of vacuum and the oxide-free gas prevent intergranular oxidation in the part. Acetylene, when used as a carburizing gas, provides a high dissociation rate in the pertinent temperature ranges of 1650-1900°F (900-1040°C). It is able to carburize densely packed loads with large surfaces, thereby improving productivity. Vacuum carburizing is distinguished by a very high carbon transition into the workload, clearly reducing process times as compared to atmosphere gas carburizing.

A typical vacuum-carburizing process (Fig. 2) starts by heating up the parts under vacuum or convection to carburizing temperature. After the load is completely heated, the carburizing process starts by adding acetylene into the treatment chamber. Through a series of pulses – multiple repetitions of carburizing and diffusion steps followed by a final diffusion phase – the specified carbon profile is obtained. The carburizing cycle parameters are calculated within a process-simulation software package to determine the various pulse and pause times as well as the necessary carburizing-gas flow. Since the rate of carbon diffusion is mathematically predictable, the recipes developed include a very high rate of accuracy. Following the final diffusion phase, the parts are cooled to a lower temperature and then quenched using high-pressure gas.

Repetitive (Predictable) Process

Unlike atmosphere carburizing, vacuum carburizing cannot practically include in-situ carbon gas-analyzing equipment. Fortunately, this is not necessary for the continuous, highly repetitive processing required in the transmission industry. Vacuum carburizing is a very safe and repeatable process. It is a recipe-controlled, not an atmosphere-controlled, process. Prior to continuous operation, recipes are

Fig. 1. Gear components for the automotive industry

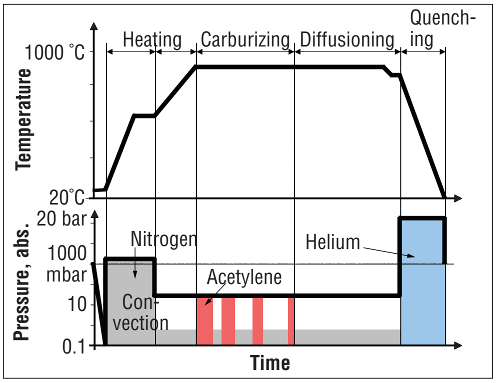

Fig. 2. Schematic process flow

created using the simulation software mentioned above. This establishes the process parameters such as temperature, pulse/pause times, carburizing-gas volume and process pressure. All of these parameters are controlled and monitored during the process. Additionally, carburizing samples may be used in serial production for additional testing of the carburizing results. By simply weighing these samples before and after the case-hardening process, a cost-efficient and prompt evaluation of the carburizing results is possible.

By using higher carburizing temperatures, increased throughput can be achieved. However, the temperature in most of the atmosphere gas-carburizing systems cannot exceed 1830°F (1000°C) for any sustained durations. Vacuum-carburizing systems are well-suited for this temperature range by virtue of the materials used in their construction. Actually, the temperature possibilities are limited by the case-hardening steel currently used in transmission technology. These steels can be susceptible to grain coarsening at high temperatures. New process technologies in steel manufacturing, however, allow the precise use of micro-alloying additions such as Al, Ti and Nb to produce fine-grained steel qualities.[3]

High-Pressure Gas Quenching (HPGQ)

For many years, high-pressure gas quenching has been the preferred quench method when heat treating tool steels. Through the steady increase of quench pressure and gas velocity as well as the development of suitable quench chambers, quench intensities have increased in such a way that even low-alloyed case-hardening steels and heat-treatable steels can be hardened successfully. When compared to liquid quenching, HPGQ also has ecological and economical advantages. The quench gases used – nitrogen and helium – are inert and leave no residue on the parts. It's not necessary to invest in post-quench washing machines or elaborate fire-prevention systems. Using a quench-gas recovery system significantly reduces gas consumption, which in turn reduces heat-treatment costs. Contrary to liquid quenching, there are no quenchant phase transitions in gas quenching. The heat transfer is more homogeneous, which is a precondition to minimizing distortion in shape and size during quenching.

The use of vacuum carburizing increased significantly during the mid-1990s as a result of combining a now reliable vacuum-carburizing process with high-pressure gas quenching. In low-alloyed case-hardening steels it became necessary to limit the materials used as a result of their hardenability scatter band towards higher "harden-abilities" (so-called HH qualities). This obtained the specified tooth-root strengths, especially in small- and mid-sized gears cut from low-alloyed steels such as 16MnCr5, 20MoCr4 and 20NiCrMo2. In these materials, tooth-root strength of more than 300HV can only be obtained by using 20-bar helium quenching. Higher-alloyed steels such as 20MnCr5 and 18CrNiMo7-6 can be gas quenched using nitrogen. The spread of the new case-hardening technology forced steel manufacturers to begin development of modified or "new" steel qualities for gas quenching. Here, the critical quench intensity could be reduced by the use of alloy additions to enhance hardenability – Cr, Mn, Ni and Mo – in order to safely harden, for example, solid commercial-vehicle transmission parts (Fig. 3).

(Left) Fig. 3. Large crown wheels of commercial vehicles. (Above) Fig. 4. Ring gears of 6-speed automatic transmission loaded on CFC grids.

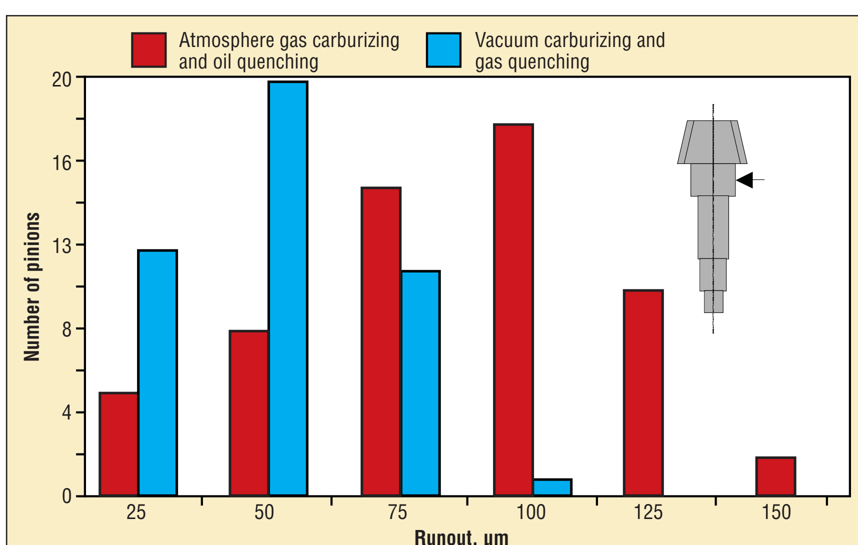

Fig. 5. Reduction of run-out distortion of vacuum-carburized and gas-quenched bevel-gear pinions

As previously mentioned, part distortion can be reduced by gas quenching in lieu of oil quenching. This results in the reduction or even elimination of the costs associated with hard (post heat-treat) machining, thereby leading to a significant reduction of the total production costs. In recent years, testing efforts have led to the full exploitation of this technology and to the development of new gas-quenching processes. As a result, ring gears for 6-speed automatic transmissions, which are highly susceptible to distortion, are now processed using special fixtures made of carbon-fiber-reinforced carbon (CFC) and quenched in a free gas flow in a step-by-step quench process called "dynamic quenching" (Fig. 4). Subsequent post-heat-treat machining is no longer necessary.[4]

Another example of parts susceptible to distortion are pinions where significant run-out distortion occurs during oil quenching. These parts are normally straightened in an additional process step, bearing the risk of cracks resulting in scrap parts. The change from oil quenching to gas quenching led to a significant reduction of run-out distortion and dispersion, reducing straightening work and the risk of crack formation (Fig. 5).

Modular Heat-Treatment Systems – ModulTherm®

Heat treating in the automotive industry requires flexible and modular furnace technologies that provide high throughput rates. A typical example for such a system is the ModulTherm® system. These systems features up to 10 separate heat-treatment chambers arranged successively. The system processes loads of up to 2,200 pounds (1,000 kg) by a transport module that runs on rails.

The chambers are cold-wall furnaces, meaning they do not radiate heat and remain under vacuum and process temperature during normal operation. The overall dimensions of the workload are 40 inches long x 24 inches wide x 30 inches tall. The extra height better enables processing of long shafts or multiple-layer loading. Of course vacuum processing also means the furnaces are off during down times (not idling as in atmosphere furnaces), and they come up to temperature quickly when operation is desired.

The mobile-transport module loads and unloads the treatment chambers. The transport module consists of a transport chamber equipped with a forklift system. Further, it supports the high-pressure gas-quenching chamber, where loads are quenched in a gas flow following the heat-treating process. The transport module is supplied with the necessary utilities – power, gas and cooling water – which are installed in an energy chain. For quenching, the quench chamber is positioned in front of the respective treatment chamber. The load is transported into the quenching chamber and subsequently quenched by an intensive gas flow. The treatment chamber is reloaded while the charge cools in the quench chamber, thereby increasing the total system throughput.

Operating Experience in the Powertrain Industry

Flexibility

Many positive long-term experiences have been reported regarding the use of the ModulTherm system in the continuous batch production of transmission parts. The inherent flexibility of the system is easily apparent to the heat treater in the planning stages. The system is designed to grow in output as heat-treat volumes ramp up by simply starting with fewer treatment chambers and increasing the number to meet the ultimate production rate. The ability to increase the number of treatment chambers, if needed, helps to reduce the investment risk and capital commitment at the onset. These capacity expansions are performed with minimum interruption and take only a few days to complete.

The ModulTherm process flexibilities are especially beneficial if different transmission parts are to be processed in one system. For example, synchronizers with a shallow case of 0.3 mm, gears with a medium case of 0.6-0.8 mm and shafts with a deep case of more than 1 mm can be treated in one system with individual, optimally adapted carburizing parameters. Quenching parameters can also be adapted for the respective requirements. Thus, the rather thin-walled synchronizer rings are quenched with a low quench pressure or by using "dynamic quenching" routines – a step-by-step quench intensity that has very positive effects on distortion. The gears are hardened using high-pressure gas and velocity in order to obtain the required tooth-root strength. If the parts are charged in several layers, alternating gas flow (top-to-bottom or bottom-to-top) assures minimal dispersion of the tooth-root strength of parts within the load. Shafts are quenched in either standing or hanging positions, and the gas flow is typically from top to bottom exclusively. Gas pressure and gas velocity are adopted to reduce run-out (Fig. 6).

Process Capability, Machine Capability

The process parameters required for continuous production of transmission parts are determined in advance. The optimal process parameters of each part are saved

Fig. 6. Long gear shafts

in the control systems as heat-treatment recipes. Due to variations in the ingot material (melt, pre-heat treatment) the heat-treating results may show deviations even when using the same recipe. Based on your quality requirements it may be a good idea to do a "pre-run" on a new material charge in order to adjust the parameters for soft machining accordingly.

Vacuum heat-treat systems are often integrated into the production lines. They must therefore meet the demands of quality control in view of process capabilities.[5] It is essential to understand that heat-treat results are influenced by numerous factors that cannot be controlled by the actual heat-treatment process itself.

As an example, inhomogeneities in the base (ingot) material or complex residual stresses induced during soft machining may result in post-heat-treat microstructure or distortion issues. This can lead to low process-capability factors in spite of a high-quality heat-treatment process. Another potential problem is the quality control of the heat-treated parts. This can be very costly and time-consuming, and the measuring methods are not as precise as the examination of geometric dimensions following mechanical machining. For these reasons, many users do not apply process-capability studies to their heat-treatment operations. Others extend the tolerance ranges of metallurgical and dimensional parameters to achieve the demanded process-capability factors.

Technical Availability, Degree of Utilization

For obvious economic reasons, a high level of equipment availability and a high degree of utilization are essential for large batch-production systems. This is particularly necessary for heat-treatment systems that are integrated into the transmission production chain. In "just-in-time" production, buffers don't exist to compensate for potential furnace breakdowns.

The modular system offers a high degree of total utility of >90% and a technical availability of >95%. In case of a failure during the treatment process, the respective treatment chamber can be removed from the production process without interfering with the remaining system's operation. For maintenance and repairs, the treatment chamber is cooled down and the actual heating chamber becomes accessible via a large rear door. Upon completion of the repair, the chamber is closed, evacuated, heated and re-integrated into the complete production within a very short time. The design of the main components – transport module including gas-quench chamber – ensures that all drives are installed externally and are easily accessible. When maintenance is required, the transport module is moved to a special maintenance position where maintenance or repairs can be performed within a short time, and it can then be returned to the production operation.

Fig. 7. PM sprockets (Stackpole Ltd.)

Operating Efficiency

When making decisions for investment in an automated heat-treatment system, operating efficiency naturally plays an important role. The new heat-treatment technology is competing against the well-established atmosphere gas-carburizing technology with oil quenching. Unfortunately, only the actual heat-treatment costs are taken into account in this comparison without considering the costs for the entire transmission production chain. This is absolutely necessary, however, if the furnace systems are to be integrated into a production line. Surely the capital investment costs for an automated system are higher in vacuum technology than in atmosphere technology. However, and to the contrary, vacuum-system operating costs are considerably lower. An exact efficiency comparison of both technologies is only possible for an actual application, taking into account all conditions.

Process Flexibility

ModulTherm permits a number of various processes. Currently, the majority of the installations are used in the powertrain industry to case harden transmission parts by vacuum (LPC) or carbonitriding.

In addition to forgings, powder-metal (PM) materials are widely used for transmission parts (Fig.7). Treatment of these parts in atmosphere-carburizing furnaces with oil quenching, however, has a number of disadvantages. High porosity prevents the formation of the required carburizing profile. The large surface area of PM parts demands a great deal of atmosphere control in the furnace, especially where chromium-alloyed PM parts are concerned. Further, the open-pored surface requires a significant cleaning effort after oil quenching.

Vacuum carburizing and gas quenching of PM parts therefore offer some rather obvious advantages. Figure 8 shows a Modul-

Fig. 8. ModulTherm® system for vacuum deoiling and carburizing of PM sprockets

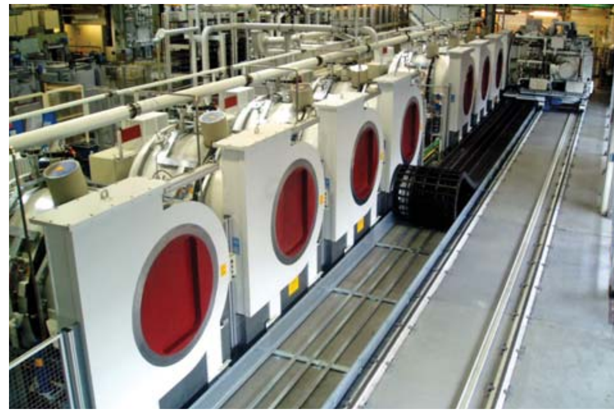

Fig. 9. Fully automated 8-chamber ModulTherm® for vacuum carburizing and gas quenching of bevel-gear pinions (BMW)

Therm plant with six treatment chambers in which PM sprockets are case hardened. At first, oil residues from the mechanical calibration process are removed from these parts. This is done in three treatment chambers, where the parts are de-oiled using temperature and vacuum. Then the parts are transferred by means of the first transport module into one of three carburizing chambers, where they are vacuum carburized. Subsequently, quenching is performed in a transport module with integrated gas quenching under helium up to 20 bar.

The new heat-treatment technology is also applied in the case hardening of bevel-gear pinions in axle drives. Figure 9 shows a fully automatic case-hardening plant based on the ModulTherm system with eight treatment chambers. The pinions made of 16MnCr5 (SAE 5115) are carburized with acetylene in vacuum and quenched in 20-bar helium. An external transport system connects the system with the pre-oxidation furnaces, a tempering furnace and a load-buffering station, thereby enabling continuous unmanned operation through the weekends. A master control system maintains fully automatic control and monitors the entire heat-treat process.

The examples mentioned show the advantages of flexible, modular heat-treat systems that have proven themselves against continuous systems in the market. To this point, more than 100 heat-treat systems with more than 600 treatment chambers for continuous, automated production of gear components are operating in the powertrain industry, and the market for this new heat-treat technology continues to grow. While gearbox performance requirements tighten, heat-treat systems for technologies like 6-speed automatic or dual-clutch gearboxes must answer the need.

Summary

Vacuum carburizing in combination with high-pressure gas quenching is an innovative heat-treat technology on the rise in the powertrain industry. It is distinguished by the following features:

- High carbon transition – short process times
- Intergranular-oxidation-free parts
- High carburizing uniformity and reproducibility
- Low process-gas consumption
- Simple process control
- Low energy consumption
- Low distortion
- Bright, clean parts
- Selectable quench intensity
- Suitable for integration into production lines

Flexible and modular furnace systems like ModulTherm have demonstrated to be well-suited for production-integrated heat treating in the powertrain industry. IH

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