In-line, High-volume, Low-distortion, Precision Case Hardening for Automotive, Transmission and Bearing Industry

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Abstract

Gears and bearings are part of mechanical power transmission devices used in machinery and vehicles. They are produced on a massive scale, and for the automotive, transmission and bearing industry and global annual output reaches billions of pieces. Gears are commonly made of steel and have teeth with a hard surface and a flexible core which provides suitable strength and service life. These properties are usually obtained by heat treatment often on the basis of carburizing and quenching. In addition to the positive effect on the mechanical properties, heat treatment is related to deformation hardening, which negates the quality and significantly increases the costs of production while corrective hard machining is applied. For this reason, the aim is both to minimize distortion and to increase the precision and repeatability of the process results particularly in mass production.

A single-piece flow case hardening system based on low pressure carburizing (LPC) and high pressure gas quenching (HPGQ) will be presented. The system allows individual adjustment to the size and shape of the particular part in order to minimize hardening distortion and ensures ideal repeatability of results throughout the parts series. It is a compact system designed for high-volume heat treatment of parts in a lean manufacturing configuration ready for implementation within machining centers.

Introduction

Global output of the automotive industry reached about 90 million vehicles in 2015. Each vehicle is fitted with a transmission gearbox. 90% of these gearboxes are traditional automatic or manual with gears being the main component. Modern transmission have multiple gears for each step as well as other parts such as drive shafts, synchronizing rings and bearings (Fig. 1). Including secondary market, global output of gears in the automotive industry is estimated to be approximately 1 billion gears per year. In addition there are millions of bearing rings which are case hardened especially for medium and large size machinery.

While the automotive industry is the largest manufacturer of gears, it is not the only. There are a wide variety of gears produced for other types of machines and vehicles as well. Beyond gears, there are other steel parts that will be produced, such as several hundred million drive shafts, all requiring case hardening [1].

Case hardening by carburising is one of the most common methods of thermal, or rather thermo-chemical, treatment. It involves diffusive infiltration of carbon from the surface inwards and subsequent quenching, then tempering (Fig. 2) [2,3]. This produces a very hard and surface abrasion-resistant element, while at the same time maintaining a flexible core, capable of carrying large, impact loads. The most common steels for carburizing are the EN 16MnCr5 or 20MnCr5 (AISI/SAE 5115, 5120, 8620) grades, their equivalents, or slight modifications. Heat treating produces a typical effective case depths of 0.4-2.5 mm (0.017-0.10 in) and surface hardness of 58-62 HRC and a core hardness exceeding 30 HRC [4].

Typically, case hardening results in the dimensional deformation of the gear caused mainly by a change of the steel structure volume resulting from austenite transformation and lack of uniformity of process parameters during the heating process, especially quenching. Distortion can also be exacerbated by non-homogeneous incoming material or by stresses created during initial machining. Distortion also depends on the geometry of the part. Since the dimensional integrity of the gear, and especially the teeth, is essential for its
life, efficiency, and vibration and noise reduction, any post-
heat treat distortions are corrected by relevant methods, e.g.,
grinding. These deformation corrections are one of the most
costly processes in gear manufacturing because it requires very
high dimensional precision and requires costly tools for hard
machining. [5-9].
An analysis of the cost for removing quenching deformations
performed in 1995 by IWT (Institut fur Werkstofftechnik)
Bremen for the German industry determined the cost to be
approximately 850 million Euro per year in the automotive and
gearbox industry and 1 billion Euro per year in the bearings
industry [10]. Extrapolating this data to the global industry and
taking into account the 20-year production increase, the
current estimated cost to correct post-heat treatment
deformation is roughly 20 billion Euro per year. It is a great
burden for the industry and a great opportunity for savings.

**Traditional mass production case hardening**

**Atmospheric Case Hardening Furnaces**
The case hardening process is usually conducted in an
atmospheric furnace using an endothermic atmosphere
followed by an oil quench. These furnaces can vary in size
from as small as a batch integral quench furnace capable of
processing approximately 100 kg (220 lbs) gross per hour, up
to semi- and continuous furnaces such as: pusher, rotary
hearth, roller hearth furnaces capable of processing over
2,000 kg/h (4,400 lbs/h) (Fig. 3). These larger capacity
continuous furnaces are typically used in the mass production

![Fig. 3. The roller heart furnace.](image)

Carburizing in endothermic atmospheres has been known for
dozens of years and the process is properly controlled with
oxygen probes and gas analyzers. However, it carries with it an
inherent defect: intergranular oxidation (IGO), which is caused
by the presence of oxidizing gases (CO₂, H₂O, O₂) in the
atmosphere. Surface grinding is required to remove the
dangerous IGO imperfections to the depth of as much as
several dozen µm, and this removal comes at a high cost [4].

Moreover, carbon transfer in endothermic atmospheres is not
especially effective (several dozen g/m²). In order to
compensate for this poor transfer, large amounts of the carbon-
carrying atmosphere must be supplied to the furnace – from
one to over a hundred m³/h depending on the furnace size and
surface to be carburized.
The overall cost of heat treating in an endothermic atmosphere
is relatively high. Fuel is consumed not only to create the
atmosphere but additional fuel is consumed to bring and keep
the newly introduced atmosphere up to the appropriate
temperature within the furnace. Continually introducing and
heating the atmosphere consumes additional energy. This and
the fact that much of the atmosphere is exhausted contributes
to the systems overall inefficiency.

Endothermic atmosphere carburizing also carries with it the
inherent risk of fire and explosion and numerous costly safety
procedures must be followed to mitigate the risk, not to
mention the environmental issues associated with emissions
[12-14].

Quenching, which in most cases is done in oil, is an important
stage of the case hardening process. Oil is a commonly known
quenchant with known disadvantages arising from the 3-phase
nature and speed of quenching and the uncontrollability of
the process. If one takes into account that each phase appears at a
different time in different places on the part being quenched,
large and unique deformations associated with oil quenching
are obvious. Additionally, parts need to be washed after
quenching in special washers where chemicals are used which
are increasingly problematic with respect to environmental
regulations.

Continuous furnaces can occupy hundreds of square meters of
valuable floor space. Because of the large size of these
furnaces, changing the process parameters and stabilizing the
working environment takes hours. Switching these furnaces
on/off takes weeks. Any interruption of the production process
results in huge energy and production losses.

**Vacuum Case Hardening Furnaces**
In response to the above listed weaknesses of traditional case
hardening technologies, low-pressure carburizing (LPC) and
high-pressure gas quenching (HPGQ) technologies were
developed in the 1970’s/1980’s. By the 1990’s, the
technologies had been perfected enough to find industrial
applications, including mass production industries like the
automotive industry. Currently, LPC and HPGQ carried out in
vacuum furnaces, have effectively replaced traditional
atmosphere furnaces. These new LPC/HPGQ furnaces include
batch, semi-continuous, and modular systems for mass
production (Fig. 4, 5) [15].

Low-pressure carburizing overcame the weaknesses of
endothermic carburizing and added a range of new
possibilities. IGO was eliminated because of the total absence
of oxygen in carburizing gases. Carbon transfer effectiveness
increased about 20 times, considerably decreasing atmosphere
consumption. Moreover, the atmosphere in the furnace is
neither flammable nor explosive due to its low density. LPC is
also characterized by the extraordinary capability of the
atmosphere to penetrate and uniformly carburize parts with
Furthermore, HPGQ significantly improved the outcome of the quenching process by decreasing the deformation rate. Gas quenching is a single-phase process and a more uniform process with respect to a single part. Moreover, quenching rates can be regulated freely by a change of gas pressure (density) and velocity (fan rotation), thereby making the process totally controllable. Modern HPGQ systems with nitrogen or helium under 25 bar pressure are equivalent to oil quenching. As an added benefit, gas quenching eliminates the process of washing making it a much more environmentally friendly process [17].

LPC/HPGQ vacuum furnace systems are compact, energy efficient and environmentally friendly devices. They are flexible, can be switched on and off at any time, and take about 1 hour to make production ready. Moreover, they do not require atmosphere stabilization and process parameters can be changed virtually instantaneously. The case hardening technology implemented in modern vacuum furnaces is a precise, efficient, clean and environmentally friendly process [18-23].

**Characterization of Batch Case Hardening**

Although there are many benefits to these new technologies (LPC & HPGQ), there is one feature that remains unchanged. Even in new LPC/HPGQ vacuum furnace systems, parts are configured and processed in batches on special fixtures (Fig. 6) and undergo the whole case hardening process in such a configuration. This means that each part in a batch is affected by the process conditions in a unique manner based on its position within the batch. Each part is affected differently regarding the heating rate, composition of the process atmosphere, and intensity and direction of cooling medium. There is no doubt that the parts in outer layers of a batch are heated more quickly and to a different temperature (according to the temperature distribution within the batch), the atmosphere around them is “richer” and they are quenched more intensely compared to the parts toward the center of the load. The result is that parts inside the batch have different physical and metallurgical properties than those on the outside of the batch, e.g., surface and core hardness, microstructure, and especially the effective case depth [24-26].

<table>
<thead>
<tr>
<th>Case depth [mm] [inch]</th>
<th>925°C</th>
<th>950°C</th>
<th>980°C</th>
<th>1000°C</th>
<th>1020°C</th>
<th>1040°C</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>0.50 0.02</strong></td>
<td>1h23m</td>
<td>0h57m</td>
<td>0h39m</td>
<td>0h30m</td>
<td>0h24m</td>
<td>0h19m</td>
</tr>
<tr>
<td><strong>1.00 0.04</strong></td>
<td>5h30m</td>
<td>3h50m</td>
<td>2h35m</td>
<td>2h00m</td>
<td>1h35m</td>
<td>1h15m</td>
</tr>
<tr>
<td><strong>2.00 0.08</strong></td>
<td>22h00m</td>
<td>15h10m</td>
<td>10h20m</td>
<td>8h00m</td>
<td>6h10m</td>
<td>4h50m</td>
</tr>
</tbody>
</table>

| Time relations      | 100 % | 69 %  | 47 %  | 36 %   | 28 %   | 22 %   |

**Tab.1. Carburising time of 16MnCr5 for the given case depth with criterion of 0.35%C, depending on the temp.**

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Fig. 4. Semi-continuous, vacuum, three-chamber, LPC with oil quench furnaces.

Fig. 5. Multi chamber, rotary system, LPC with HPGQ.

Fig. 6. Example of gears configuration in a batch.
In an analysis of the effect of the carburizing temperature on the effective case depth, a typical parameter of the temperature uniformity was adopted: +/- 6°C (+/- 10°F) for a class II furnace in accordance with AMS 2750E. Taking as an example the temperature of 950°C (1742°F) for a 0.75 mm (0.03 in) case (for the 0.35%C criteria), the effective case depth obtained at 944°C (1731°F) was 0.72 mm (0.03 in), whereas at 956°C (1753°F), 0.78 mm (0.033 in). The difference between the effective case depths is 0.06 mm (0.003 in) (8%) for the temp. dispersion of +/- 6°C (+/- 10°F).

Similarly, the composition of the carburizing atmosphere is not uniform and it changes as the atmosphere moves toward the center of the batch with the amount of carbon decreasing gradually and, in consequence, poorer carburization of the parts at the center of the batch. The differences in the atmosphere composition (carbon potential) can be as great as 10% and the case depth can change accordingly.

The cooling rate during the quenching process also affects the case depth with a faster quench increasing the case depth and a slower quench decreasing the case depth. Non-uniformities of the cooling medium flow rate through the batch can be as high as 50% and can also significantly impacting the case depth by several more percent [17].

Due to the compounding effect of these varying parameters inherent in batch processing, it is not surprising that the industry's quality expectations are very liberal. Tolerances can be as high as 50% (0.6-0.9 mm or 0.025-0.038 in), a direct consequence of batch processing and the currently accepted tolerances of the batch processing case hardening systems. The intensity and uniformity of parts quenched in batches is a separate issue. Intensity of quenching determines the hardness of the core and the effective case depth, and the uniformity determines the dispersion of those parameters across parts within the batch and, what is most important, the size of quenching deformations on individual parts. Batch quenching has one important common feature. Regardless of the device or the cooling agent (liquid, gas), batch quenching is a single-direction cooling (what we will call "2D"). This means that an individual part is affected by the cooling agent which flows in one specific direction (from top to bottom or from left to right, etc., with the flow not necessarily linear). In consequence, the part cooling rate is different in different places on the part. Non-uniform quenching results in temperature gradients within each part resulting in thermal stresses and a non-uniform transformation of the microstructure. This ultimately results in large deformations of the part being quenched. Quenching results are made even worse by the fact that the quenching stream within the batch is dispersed and each part is cooled differently based on its position within the batch. A critical summary of batch 2D quenching (especially oil quenching) shows that it is an uncontrolled and non-uniform process producing great deformations within each part and little consistency within the batch. Using gas as the quench media can reduce deformations within each part compared to oil due to the single-phase nature of convection cooling with gas, but all the variations within the batch still remain [27].

Batch processing also has other quality, material handling, and cost pitfalls. For example, monitoring and reporting on the case hardening process is for the entire batch and not for individual pieces within the batch. That makes it difficult, or even impossible, to introduce and implement tighter quality standards.

Material handling of batch loads is typically complicated and costly. Gears are produced individually. After being shaped, they are collected, packed, protected, and transported to the case hardening department (captive) or to an external plant (commercial) which can range from hundreds of meters to hundreds of kilometers away. The gears are then unpacked, washed and racked to form batches on fixtures designed specifically for the case hardening process. Following an oil quench, the parts are washed again, dismantled, packed, protected, and transported back to the mechanical processing department. The whole undertaking may be divided into more than ten operations and take days. These material handling costs consume considerable resources including time, materials, and money.

It is critically important to have special fixtures for case hardening and these fixtures are typically made of heat-resisting Ni-Cr alloys. The price of a medium-sized fixture starts at thousands of Euros and the lifespan ranges from 2 to 4 years. Considering the fact that the largest installations require over 100 sets to ensure continuity of the production process, the cost of fixturing alone can reach thousands of Euros a year. The fixturing also affects the amount of direct energy consumption costs because it accounts for 40-50% of the overall batch weight, thereby generating higher consumption of energy needed to heat up and cool down parts.

The current technology must be appreciated for its huge productivity and minimal per-piece cost. The technology has been used and improved for decades and sufficiently mastered. Because of the nature of the process, the ability to further develop and improve the process has hit a wall. Specifically, the increasing needs and expectations of the industry in regard to per-piece quality improvements and reporting, repeatability, flexibility, speed, process continuity, reduction of the total costs of production and neutrality to the environment cannot be satisfied with traditional methods.

A new approach to case hardening technology is needed. This new technology will not only fill the existing gap, but will provide a solid foundation for future development. Specifically, a new approach is needed that will:

- Improve accuracy, precision and repeatability
- Reduce quenching deformations
- Integrate case hardening equipment into continuous production lines

**New approach to case hardening**

**Single-Piece Flow Case Hardening**

The vast majority of weaknesses and limitations of the current case hardening processes are associated with its batch-related nature. Therefore, to eliminate these weaknesses and limitations, it would be ideal if batch processing was eliminated and replaced with a continuous, single-piece flow model. The single-piece flow concept has been around for some time in theory, industry articles, lectures and
presentations [28,29]. Various systems, more or less in line with the idea, have been developed, but no device for mass thermal treatment has been constructed that would fully embody the idea to-date. Single-piece flow processing should mean that every single piece goes through the exact same positions and process conditions as every other piece. A system where parts are placed on trays, even in single layers, or when parts are processed individually in different process chambers, does not meet the criteria of a single-piece flow system.

UniCase Master®

Fig. 7 shows a vacuum furnace for case hardening of gears or rings using LPC and HPGQ. This system fully meets the criteria of a single-piece flow method and has all the accompanying advantages. The furnace consists of three horizontal chambers: the first one for heating up, the second for low pressure carburizing, and the third for diffusion and pre-cooling before quenching. Additionally, a separate loading chamber and a quenching chamber that doubles as an unloading chamber are connected. Parts are transported between chambers by two vertical transport elevators attached to each sides of the system.

Each gear follows in sequence and is processed the exact same way, with the exact same process parameters, guaranteeing the highest level of precision and repeatability.

Precision and repeatability improve because each part runs individually and is exposed to the exact same temperature and atmosphere. Single parts heat up more quickly and more uniformly due to direct radiation and the beneficial effects this direct radiation has on the more consistent conduction of heat within the gear. Moreover, any temperature gradients within the chamber are neutralized because each part goes through all the same positions. It is possible to achieve temperature uniformity as tight as +/−1°C. The same is true of the process atmosphere which directly reaches the part surface consistently. Even if the atmosphere composition varies in different places within the chamber, the average value after each gear has gone through all positions is the same. Considering the above, it is conceivable to achieve a uniform and repeatable carburized case depth in a single part and consistently throughout the batch as good as of 5% spread.

4D Quenching®

UniCase Master® also allows for significant improvements in the quenching process, specifically the reduction of distortion. This is done primarily using a high-pressure gas quenching system installed in the quenching/unloading chamber (Fig. 8).

The system utilizes a proprietary arrangement of cooling nozzles that surround the part and ensures a uniform flow of cooling gas from all sides; top, bottom, and side. We refer to this as “3D” cooling. In addition, a table spins the part further enhancing quench uniformity. We refer to the spinning motion as the fourth dimension allowing us to “4D” quench gears for the best possible uniformity. The cooling nozzles allow us to achieve 15 bars quenching results – comparable to oil quenching – without the use of helium (He). Because the cooling nozzles can be adjusted to exactly fit the gears precise size, quenching is optimized and distortion significantly decreased. It is anticipated that, compared to oil quench systems, quenching deformations rates for each piece and across the entire batch will easily be cut in half.
Technical and Technological Assumptions
The UniCase Master® system was designed using the following criteria for the automotive industry:

- Part diameter/high: 200/50 mm (8.0/2.0 inch)
- Weight: 3.0 kg (6.6 lbs)
- Tact: 60 sec

Number of parts: 15 (in each process chamber)

A gear with a diameter of 200 mm (8 in) and weighing 3 kg (6.6 lbs) covers all the gears in passenger car and most truck gearboxes currently manufactured. The optimum duration of the loading-unloading cycle was 60 seconds which corresponds well to the production cycle of CNC machine tools. An analysis of the part’s heating rate and the process of carburizing for 0.4-1.0 mm (0.02-0.04 in) case, required process chambers with 15 index positions. As a consequence, each part has a residence time of 15 minutes in each process chamber. It has been proven that parts can be heated-up in 15 min then the processes of carburizing and diffusion at 1040°C (1904°F), where a carbonized case of 0.6 mm (0.025 in) can be obtained during 30 minutes cycles. The example above is only one example. Other cycle durations and process temperatures can be used to obtain other required case depths.

Quenching of a single part in 4D Quenching® system is very effective. Having a heat transfer coefficient with nitrogen or helium at the range of 1000-2000 W/m²K, most of the parts can be quench in a less than 60 sec.

Lean Manufacturing
UniCase Master® is intended to be installed and operated directly on the manufacturing floor next to a CNC machine and was designed so that its footprint was similar to a CNC machine (Fig. 9). It can be installed on new production floors or at sites previously occupied by other machines, including CNC machines. A newly machined gear can be introduced into and released from the case hardening system every 30-60 seconds. The system can be completely integrated into the continuous, lean production manufacturing line, thus eliminating many, if not all, batch material handling steps.

Conclusions
Current best available case hardening technologies, both batch and continuous, fail to meet current and future expectations of high-volume automotive gear manufacturers in terms of quality, repeatability, flexibility, and integration of production as well as environmental-friendliness, and costs, mainly because parts are arranged as batches on special fixtures for thermal treatment.

The UniCase Master® system, developed to be a real single-piece flow case hardening system, eliminates the shortcomings of the current systems and is now the new “best available technology”. It meets the current and future requirements of high-volume automotive gear manufacturers and has the following features:

- Extreme precision and repeatability,
- Reduction of quenching deformations due to 4D quenching,
- Integration into continuous production lines – lean manufacturing,
- High productivity for high-volume gear manufacturers,
- Flexibility and operational speed,
- Individual part monitoring and reporting (as opposed to batch monitoring/reporting),
- Elimination of fixtures (cost, energy) and batch material handling logistics,
- Elimination of quench oils, washers and washing fluids,
- Elimination of fire and explosion hazards,
- Cleanliness of the process, no effect on the environment,
- Applying cutting edge LPC and HPGQ technologies.

These properties and advantages of the UniCase Master® system revolutionize case hardening technology and pave the way to meet the increasingly stringent quality and production requirements of high-volume gear manufacturers.
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