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UNICASE MASTER® - IN-LINE, HIGH-VOLUME, LOW-DISTORTION, PRECISION CASE HARDENING FOR AUTOMOTIVE, TRANSMISSION AND BEARING INDUSTRY

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ABSTRACT

Gears are part of mechanical power transmission devices and gear boxes used in machinery and vehicles. They are produced on a massive scale, and for the automotive industry global annual output reaches about 1 billion 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 on the basis of atmospheric carburizing and quenching in oil, realized in continuous furnaces. Traditional technology is characterized by low precision and repeatability in process results, large hardening distortion and high material handling costs mostly because of the batch type of heat treatment and inability of integration into in-line manufacturing.

There is a very strong industrial need of overcome traditional technology disadvantages and allow heat treatment meets of modern industries requirements. This article introduces an innovative and revolutionary single-piece flow case hardening system by low pressure carburizing and high pressure gas quenching which allows individual adjustment to the size and shape of the particular gear in order to minimize hardening distortion and ensures ideal repeatability of results throughout the gears series. It is a compact system designed for high-volume heat treatment of gears in a lean manufacturing configuration ready for implementation within machining centers. Additionally the article will discuss the operational aspects, process costs and productivity.

1. 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).

Fig. 1. *Mechanical transmission elements.*

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.
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). 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 grades, their equivalents, or slight modifications. Heat treating produces a typical effective case depths of 0,4-2,5 mm and surface hardness of 58-62 HRC and a core hardness exceeding 30 HRC [1].

Fig. 2. *Cross section of case hardened tooth.*

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 exasperated 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.
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 mln Euro per year in the automotive and gearbox industry and 1 billion Euro per year in the bearings industry [2]. 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 bln Euro per year. It is a great burden for the industry and a great opportunity for savings.

2. Traditional mass production case hardening

2.1. 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 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 (Fig. 3). These larger capacity continuous furnaces are typically used in the mass production automotive industry [3].

***Fig. 3.** The roller heart furnace.*

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 (CO_2, H_2O, O_2) 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 [1].

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.

Quenching, which in most cases is done in oil, is an important stage of the case hardening process. Oil is a commonly known quenchent 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.

2.2. 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).

***Fig. 4.** Multi chamber, rotary system, LPC with HPGQ.*

***Fig. 5.** Semi-continuous, vacuum, three-chamber, LPC with oil quench furnaces.*

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 shapes which make access difficult (blind holes) and densely packed loads. In addition, the processing temperature can be raised considerably resulting in shortened carburizing time – as much as 4-5 times when the temperature is raised from 925ºC to 1040ºC [4].
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.
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 [5].

3. Characterization of Batch Case Hardening

Fig. 6. *Example of gears configuration in a batch.*

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.
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% (eg. 0.6-0.9 mm), 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.,). 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. 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.

4. New approach to case hardening

4.1. 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 [6,7]. 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.

4.2. 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.

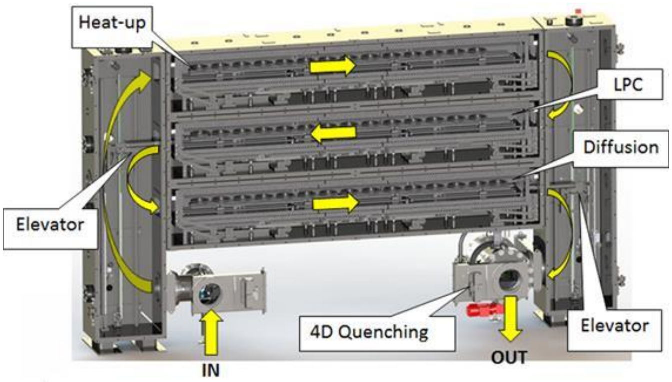

Fig.7. *The Single piece flow, case hardening System by LPC and HPGQ.*

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.
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.

4.3. 4D Quenching®

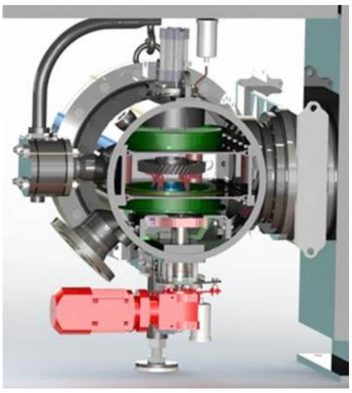

Fig.8. *4D Quenching® chamber.*

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 (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 system allows to achieve quenching results – comparable to oil quenching. Because the cooling nozzles can be adjusted to exactly fit the gears precise size, quenching is optimized and distortion significantly decreased.

4.4. 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.

It's worth to notice that the system does not use fixtures for load racking. As noted previously, this helps reduce operating costs including the cost to purchase and replace fixtures as well as the consumption of energy.

Fig.9. *The single piece flow, case hardening system integrated into in-line manufacturing.*

4.5. Productivity of Carburizing

The UniCase Master® system was designed using the following criteria for the automotive industry:

- Part diameter/high 200/50 mm
- Weight 3.0 kg
- Tact 60 sec
- Number of parts 15 (in each process chamber)

For a 200 mm diameter gear indexing 15 steps within each process chamber, a gear with an effective case depth of 0.6 mm can be produced every 60 seconds. The gear will spend 15 minutes in each chamber (for LPC in 1040°C). This results in approximate production flows of 500,000 gears/year with the continuous operation mode.

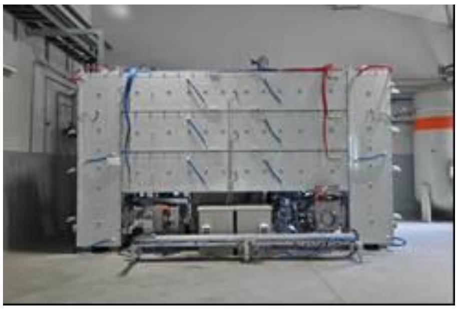

Fig.10. *UniCase Master® system.*

For gears with a smaller diameter of 100 mm and the same process requirements, system can be configured for 30 positions and the cycle reduced to 30 seconds in each position resulting in annual output of approximately 1 million parts.

4.6. Process example

The first UniCase Master® system has been manufactured and started-up already (Fig.10.). It has confirmed its technological and production performances in many trials. For example (Fig.11.): gears made of 20MnCr5, dia. 105 mm, mass 0,7 kg were case hardened according to the recipe: tact time – 60 s, LPC temperature – 1000°C (it gives: 15 min heating-up, 15 min intensive LPC and 15 min final diffusion). The process results in achieving the case depth with very low variation of 0,42-0,45 mm for the series of 40 tested gears. Every single gear consumed as low as about 2 kWh energy and 2 g acetylene for carburizing.

Fig.11. *The gear introduced to the heating chamber.*

Performed tests and results confirm very attractive features of the UniCase Master® system in terms of quality, productivity and costs. More advanced tests are in progress.

5. 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.
The UniCase Master® system, developed to be a real single-piece flow case hardening system, eliminates the shortcomings of the current systems. 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 (100% traceability),
- Elimination of fixtures (cost, energy) and batch material handling logistics,
- Elimination of quench oils, washers and washing fluids,
- Elimination of fire and explosion hazards,
- Cleanness 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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