AGMA Technical Paper

Improved Materials and Enhanced Fatigue Resistance for Gear Components

By Dr. Volker Heuer,
Dr. Klaus Loeser,
and Gunther Schmitt

ALD Vacuum Technologies GmbH
Hanau, Germany

Improved Materials and Enhanced Fatigue Resistance for Gear Components

Dr. Volker Heuer, Dr. Klaus Loeser, and Gunther Schmitt

[The statements and opinions contained herein are those of the author and should not be construed as an official action or opinion of the American Gear Manufacturers Association.]

Abstract

Key words: transmission components, case hardening, fatigue resistance, low pressure carburizing, high pressure gas quenching, case hardening steels, hardenability, grain size control

This paper shows the latest progress in steel grades and in case hardening technology for gear components.

To answer the demand for fuel-efficient vehicles, modern gear boxes are built much lighter. Improving fatigue resistance is a key factor to allow for the design of thin components to be used in advanced vehicle transmissions. The choice of material and the applied heat treat process are of key importance to enhance the fatigue resistance of gear components.

By applying the technology of Low Pressure Carburizing (LPC) and High Pressure Gas Quenching (HPGQ), the tooth root bending strength can be significantly enhanced, compared to traditional heat treatment with atmospheric carburizing and oil quenching.

Besides heat treatment, significant progress has been made over the past years on the steels being used for gear components. The hardenability of case hardening steels such as 5130H, 5120H, 20MnCr5, 27MnCr5, 18CrNiMo7-6 etc. has been stepwise increased in recent years. An important factor for fatigue resistance is the grain size after heat treatment. Therefore, grain size control is a key goal when developing new modifications of steel grades.

After enhancing grain size control, it was possible to increase the carburizing temperatures over the past years from 930°C to 980°C (1700°F to 1800°F) which resulted in shorter heat treatment cycles and thus in significant cost savings.

With the introduction of new microalloyed steels for grain size stability, carburizing temperatures can now be even further increased to temperatures of up to 1050°C (1920°F), leading to even more economic process cycles. By adding microelements such as Niobium or Titanium in the ppm-range, nitride and carbonitride-precipitates are formed. These precipitates effectively limit the grain-growth during the heat treatment process.

Improved Materials and Enhanced Fatigue Resistance
for Gear Components

Dr. Volker Heuer, Dr. Klaus Loeser, and Gunther Schmitt
ALD Vacuum Technologies GmbH – Hanau, Germany

Introduction

For decades, the gear industry has addressed the challenge to produce high-performance components in a cost-effective manner. To meet design intent, vehicle transmission components need to be heat treated. In many applications, the high demands regarding service life of components can be reached only by the application of a customized case hardening. This case hardening process results in a wear-resistant surface layer in combination with a tough core of the component.

Enhanced fatigue resistance of the components has become more and more important. This is mainly driven by the need for weight reduction and by the introduction of higher durability claims. Some vehicle OEMs have introduced a 100 000-mile warranty for the powertrain.

When trying to improve fatigue properties, two important areas need to be focused on: improvements of material and improvements in heat treatment technology. This paper describes the advances in these fields over recent years.

Improved Material

Traditionally, gear components are made of case hardening steels such as 8620H, 8625H, 5120H, 5130H, 9310H, 16MnCr5, 20MnCr5, 27MnCr5, 18CrNiMo7-6, and others. The chemical composition of a steel grade defines its hardenability, with the most important elements being carbon, manganese, chromium, nickel, boron and molybdenum. The hardenability of a steel grade can be quantified either with "DI-values" or with "Jominy-curves."

The use of DI-values is popular in North America. DI stands for "ideal diameter" and means the largest diameter of a given steel composition which under maximum quench conditions still reaches 50% martensite in the core [1]. This means that a high DI-value corresponds with a good hardenability of the steel.

The use of Jominy-curves is very popular in Europe. The Jominy hardenability curve is a standardized test as described in ASTM A255 [2] using cylindrical specimen with $\varnothing$25mm and 100mm height as test probes. After austenitizing, the probe is hung vertically and quenched with a water jet of well-defined intensity. The water jet is directed towards the lower face of the cylindrical specimen. This means that with increasing distance from this face, the quench rate inside the probe is continually reduced.

After completion of the quench, the hardness profile is measured in an axis-parallel line with 0.4mm distance to the surface. The resulting curve is the so-called Jominy-curve. This curve describes the relation between the distance from the lower face of the probe in mm or in 1/16 of an inch (so-called "Jominy-value") and the achieved hardness in HRC. Besides the experimental method as described above, the curve can be calculated from the chemical composition of the steel grade, as well. Fig. 1 shows typical Jominy-curves of case hardening steels.

15FTM02
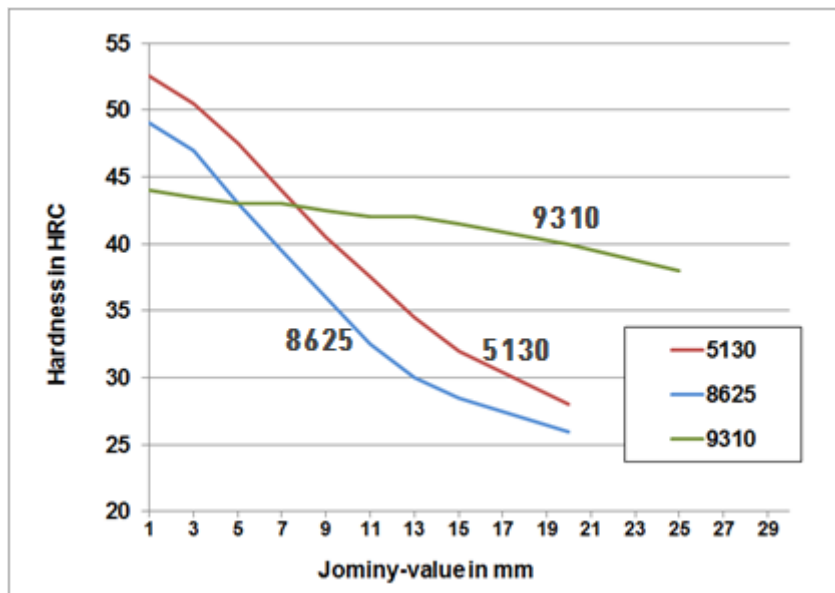
**Fig. 1 – Typical Jominy-curves of case hardening steels
(hardness as a function of the Jominy-distance)**

Each standardized steel grade has a defined range of hardenability, meaning that each grade has a minimum and maximum Jominy curve. However, many producers have restricted this range further. Doing so will result in the following benefits:

- improved distortion control;

- reduced variation of core hardness and case hardening depth (CHD) after heat treatment;

- reduced variation of microstructure (e.g. avoiding bainite formation in the surface area) after heat treatment.

Over recent years, in many applications the hardenability-range was restricted to the upper end of the standard range. The tightest range, which can be supplied by the steel industry today, is a band of 4 HRC. Fig. 2 shows an example of the grade 18CrNiMo7-6 with the standard range and with the restricted hardenability. The so-called HH-grade (high hardenability) has a range of hardenability which is restricted to the upper third of the standard range.
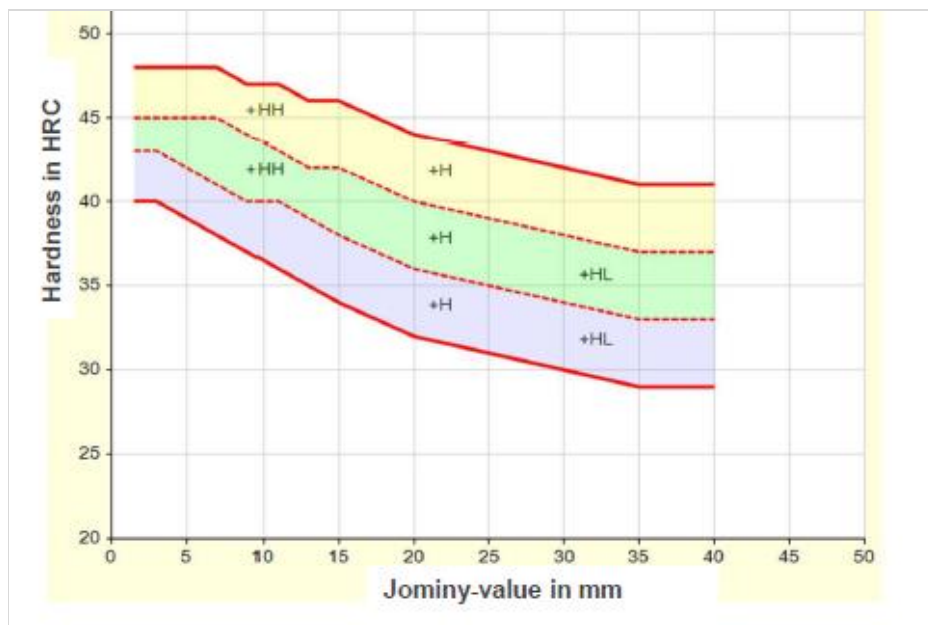

15FTM02

**Fig. 2 – Standard range and restricted range of hardenability
for the case hardening steel 18CrNiMo7-6**

In the following three examples of successful restrictions of hardenability are given.

Levers made of 8620H-material were initially supplied using the standard range with a minimum DI=1.7 inches (see Fig. 3). This resulted in significant variations of core hardness and case hardening depth (CHD). After restricting the material to a minimum DI=2.6 inches, these variations were minimized and a consistent quality was achieved after heat treatment.

Fig. 3 – Lever made of 8620H-material

Shafts made of 28MnCrB7-2-material were initially supplied in a rather wide range of hardenability with DI=2.2 to 3.4 inches (see Fig. 4). This led to significant variations in core hardness, and additionally, resulted in problems achieving consistent microstructure after heat treatment. After restricting the hardenability to a range of DI=2.7 to 3.1 inches, those variations were eliminated successfully.

Fig. 4 – Shafts made of 28MnCrB7-2-material

Final Drive Ring gears made of 4121M-material were initially supplied with DI-values ranging from 2.7 to 3.1 inches (see Fig. 5). This led to significant variations in core hardness. After improving the hardenability to a range of DI=2.9 to 3.3 inches, those variations were reduced and core hardness specification (28HRC min.) was safely reached.

Fig. 5 – Final Drive Ring gears made of 4121M-material

Advanced heat treatment technology

The high demands regarding service life of transmission components for most applications can be reached only by the application of a customized case hardening. This case hardening process results in a wear-resistant surface layer in combination with a tough core of the component. Over the past 15 years, the technology of Low Pressure Carburizing (LPC) and High Pressure Gas Quenching (HPGQ) was established in serial production. LPC is often referred to as Vacuum Carburizing as well. Typical applications include gear parts, machine components, and bearing components, as well as injection systems for engines.

The Low Pressure Carburizing (LPC) process takes place in a pressure range between 5mbar and 15mbar and a temperature range between 870°C to 1050°C. In most cases, the carburizing temperature is between 940°C and 1000°C. During the complete process, the treated components are not exposed to any traces of oxygen [3].

Fig. 6 shows the LPC process in a schematic diagram. First, the charge enters the furnace chamber under vacuum, followed by convective heating under a nitrogen atmosphere close to 1bar. Convective heating offers a quicker and more homogenous heating of the load compared to vacuum heating alone. Subsequently, another heating phase under vacuum takes place. The actual carburizing and diffusion starts after all parts have reached the specified carburizing temperature. Carburizing takes place by applying a routine of alternating pulses and diffusion-steps. Acetylene is used in most applications as the carbon source.
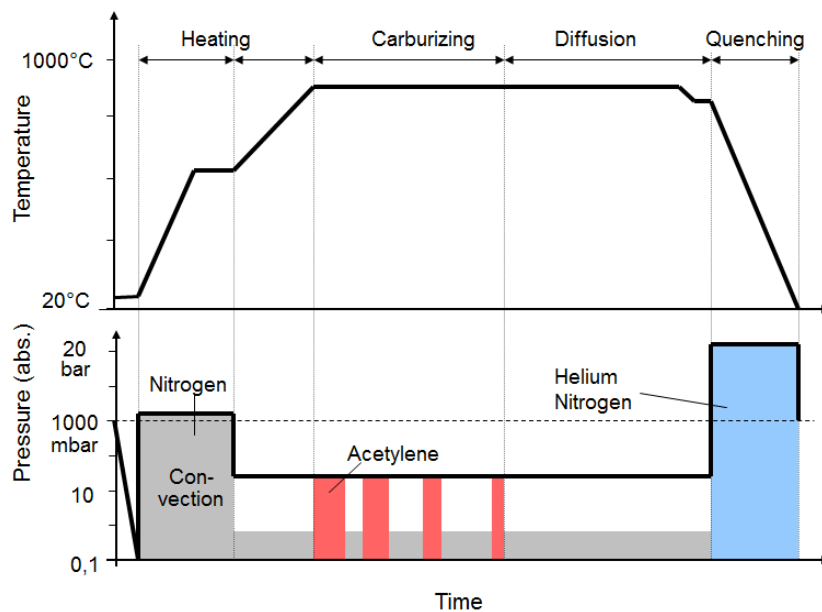
Fig. 6 – Schematic diagram of the Low Pressure Carburizing (LPC) and High Pressure Gas Quenching (HPGQ) process

Once the targeted carbon profile is obtained, the parts are quenched. Quenching can be initiated either from carburizing temperature or from a lower hardening temperature. In most cases, High Pressure Gas Quenching (HPGQ) with either nitrogen or helium is applied after LPC [4]. In a few applications, oil-quenching is applied after LPC.

Table 1 – Comparison of treatment times for LPC and Atmospheric Gas Carburizing

Application	Material	Treatment-temperature	CHD	Treatment time* LPC	Treatment-time* Gas carburizing
Internal gear	28Cr4 (ASTM 5130)	900 °C	0,3 mm	0,75 h	1,5 h
Gear	16MnCr5	930 °C	0,6 mm	2 h	2,75 h
Shaft	16MnCr5	930°C	0,8 mm	2,75 h	4 h
Gear	18CrNiMo7-6	960°C	1,6 mm	7,5 h	9,5 h

* Treatment time = Carburize+ Diffuse + Lower to hardening temperature

The high mass transfer of carbon into the components during LPC leads to significantly shorter treatment times compared to conventional gas carburizing (see Table1).

When combining LPC with High Pressure Gas Quenching (HPGQ), the process provides the following advantages compared to Gas Carburizing combined with Oil Quenching:

- excellent carburizing homogeneity even for components with complex shape;

- avoiding intergranular oxidation (IGO) and surface oxidation;

- shorter cycle times;

- potential for further reduction of cycle time when applying High Temperature LPC;

15FTM02

- possibility to integrate heat treatment into the production line [5];

- no conditioning of the equipment necessary (meaning no stepwise heating-up and no saturation of the furnace insulation necessary);

- clean surfaces of parts after heat treatment, no washing of parts necessary;

- environmentally friendly process (small consumption of resources; no disposal of oil or salt bath residues);

- potential to reduce heat treat distortion [6].

Altena studied, in particular, the field of carburizing homogeneity. Fig. 7 shows the hardness profile after LPC & HPGQ compared to Gas Carburizing & Oil Quenching [7]. When using LPC & HPGQ, the hardness profile at the root is almost identical to the profile at the flank.
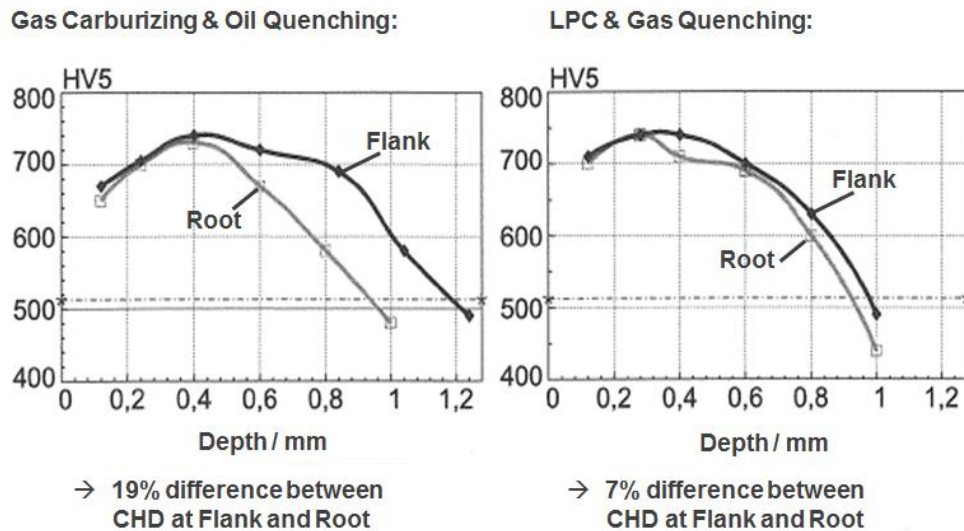

Fig. 7 – Hardness profiles of tooth flank and tooth root; comparison of Gas Carburizing and LPC [7]

In the next step, Altena studied if the carburizing or the quenching step was the deciding factor for the improvement of hardness results. Fig. 8 compares the differences in CHD between root and flank when using Gas Carburizing & Oil Quench, LPC & Oil Quench and LPC & Gas Quench. When using Gas Carburizing, the difference was 18 to 19%. When using LPC, the difference was 7 to 8%, regardless of the quench method. Therefore, Altena concluded that the carburizing step was decisive for the improved results.
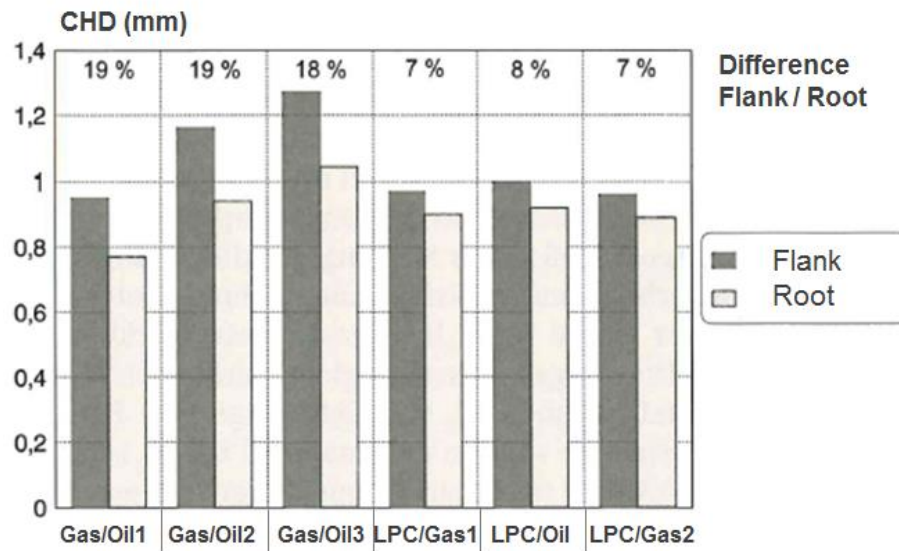
Fig. 8 – Case hardening depth (CHD) of tooth flank and tooth root; comparison of Gas Carburizing and LPC [7]

Carburizing temperature and microalloyed steel grades

The costs of the heat treatment process are largely driven by the cycle time. As shown in Table 1, the high-mass transfer of carbon into the components results in significantly shorter treatment times of LPC, compared to atmospheric gas carburizing. The advantage of LPC can be further enhanced by increasing the carburizing temperature. With increasing carburizing temperature, the diffusion rate rises sharply, and thus carburizing time is significantly reduced (see Fig. 9).

Furthermore, the limit for carbide precipitation shifts to higher values. According to the iron-carbon diagram, the precipitation limit is increased in unalloyed steel (i.e. C15) from 1.3% C at 930°C to 1.65%C at 1030°C. Consequently, high temperature carburizing allows one to target higher surface carbon contents in each carburizing pulse. The now higher concentration gradient leads to a further reduction of treatment time. This additional reduction of carburizing time is not even reflected in Fig. 9.

Table 2 illustrates the treatment times for LPC of 18CrNiMo7-6 at different temperatures for a case depth of 1.5mm. It shows that the total process time is reduced by 40% if carburizing temperature is elevated from 930°C to 1030°C.

The potential for improvement is increased with higher case depth requirements. For material 15CrNi6 and a case depth of 3mm, for example, a total process time reduction of 55% was verified when the carburizing temperature was increased from 950°C to 1050°C [8].
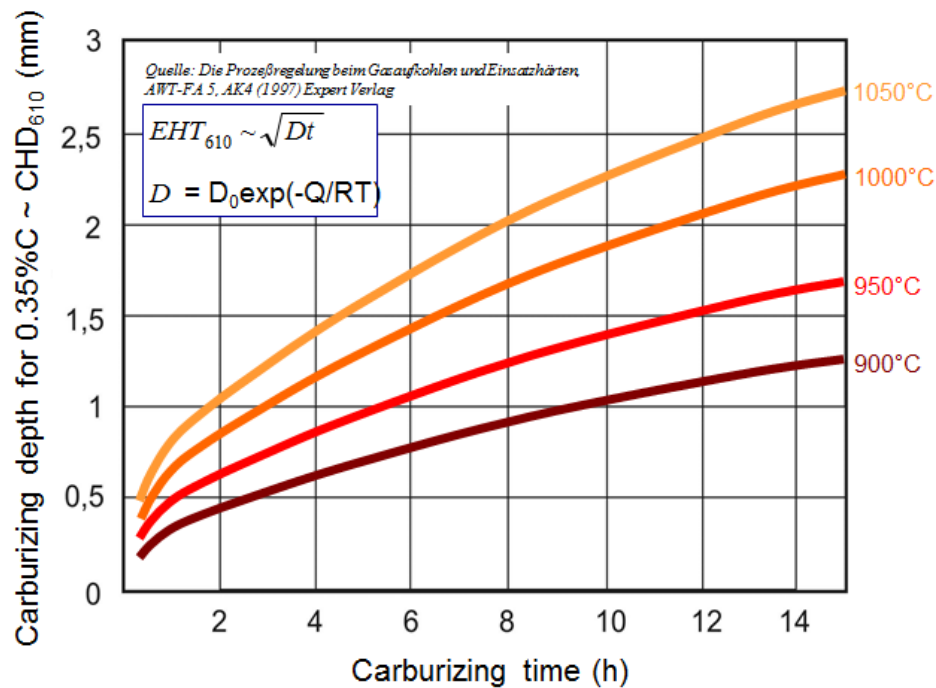
Fig. 9 – Carburizing depth as a function of carburizing temperature and duration (without heating; with case hardening depth CHD$_{610}$ = EHT$_{610}$ defined at 610 HV) [9]

The graph shows:

$$EHT_{610} \sim \sqrt{Dt}$$

$$D = D_0 \exp(-Q/RT)$$

Quelle: Die Prozeßregelung beim Gasaufkohlen und Einsatzhärten, AWT-FA 5, AK4 (1997) Expert Verlag

Table 2 – Treatment times for LPC of 18CrNiMo7-6 at different temperatures (CD = 1.5 mm)

Low pressure carburizing CD=1,5 mm - 18CrNiMo7-6		Treatment temperature		
		930 °C	980 °C	1030 °C
Loading	hrs.	0,25	0,25	0,25
Heating	hrs.	1,5	1,75	2
Carburizing and diffusion	hrs.	8,5	5	3
Lowering to hardening temp.	hrs.	0,75	1	1,25
Quenching and unloading	hrs.	0,5	0,5	0,5
Bottom → Bottom	hrs.	11,5	8,5	7
Total treatment time reduction			~ 25 %	~ 40 %

Fig. 10 shows the comparison between a conventional LPC process at 960°C and a high temperature LPC process (HT-LPC) at 1050°C. For a given CHD of 0.65mm, the cycle time is reduced from 180min to 40min. Combined with gas quenching, the HT-LPC process offers a rapid case hardening process with low values of heat treat distortion.
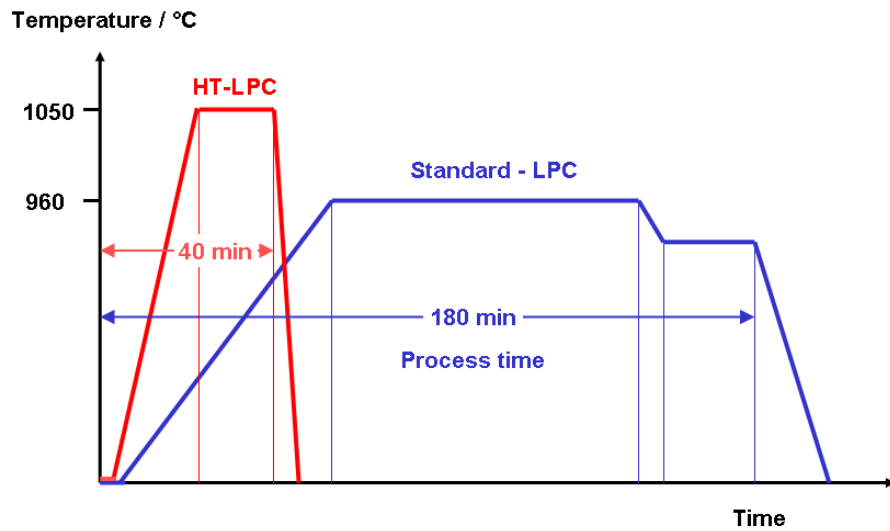
Fig. 10 – Process cycle of Low Pressure Carburizing (LPC) and High Temperature–Low Pressure Carburizing (HT-LPC); CHD= 0.65mm for both cases [5]

Over recent years, the carburizing temperatures were risen steadily (see Fig. 11). This led to enormous cost reductions and to dramatic savings of energy.
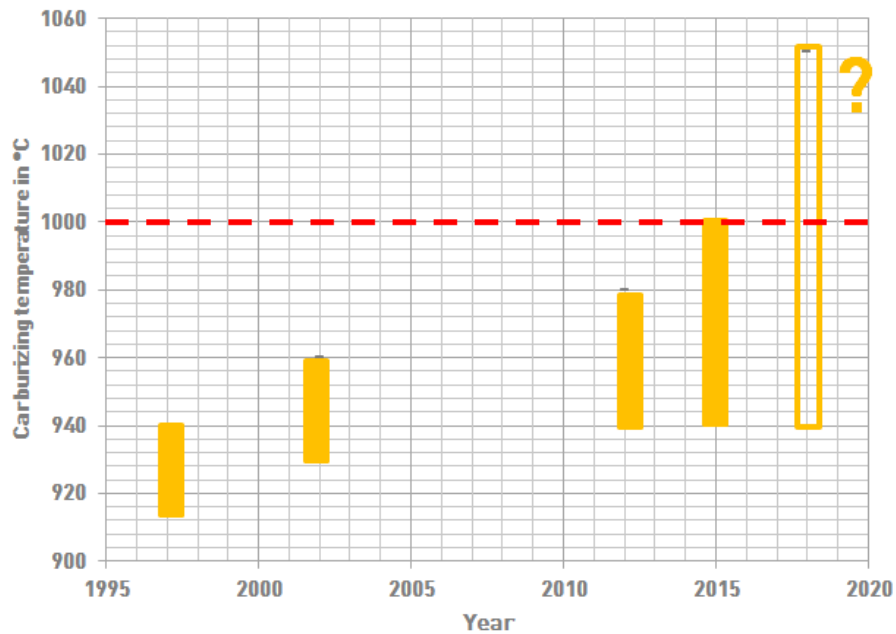

Fig. 11 – Commonly-used carburizing temperature over the past years when applying Low Pressure Carburizing (LPC)

However, when using today's conventional case hardening steels, there are limitations. When applying high carburizing temperatures above the range of 980°C to 1000°C, this may lead to an unwanted grain growth. Components with coarse or mixed grains have the following disadvantages:

- higher macroscopic heterogeneity;

- less toughness, especially in the carburized area;

- lower tooth root bending strength.

Especially for dynamically loaded parts, the formation of coarse grains can reduce service life substantially. As a countermeasure, steel suppliers started several years ago to develop new micro-alloyed steel grades to prevent unwanted grain growth [10], [11]. These micro-alloying elements form precipitates during the steel production process which act as grain boundary pinning particles and thus inhibit abnormal grain growth during heat treatment at high temperatures.

For high temperature carburizing up to 1050°C, such steels often have a controlled amount of nitrogen, N (120–170 ppm) and aluminum, Al (250–350 ppm). Furthermore, a small amount of niobium, Nb (320–400 ppm) is being added to the steel. The steel production process route is controlled in a way that an optimum size and distribution of the Al(N)- and Nb(C,N)- precipitates are being secured. Several micro-alloyed steel grades have been developed and successfully tested jointly by steel suppliers and gear manufacturers [12], [13].

Currently, several gear manufacturers are in the process of adjusting their material specifications to use these materials in high temperature heat treatment. No negative influence of micro-alloying on the gear machining processes has been reported.

Furthermore, the material needs to have a sufficient and controlled hardenability to allow for quenching with moderate quench intensities. High quench intensities should be avoided to facilitate a cost-effective gas quench process. Typical steel grades suited for that process are 20MnCr5-HH, 23MnCrMo5, 27MnCr5, 18CrNiMo7-6 or 20NiMoCr6-5, 5120, 5130, or 9310.

The use of microalloyed materials is necessary to exploit the vast potential of process time reduction through high temperature carburizing by means of LPC.

Improvements in fatigue resistance

Fig. 12 illustrates the stress distribution on running gears. The highest stress appears at the flank and the root of the teeth.
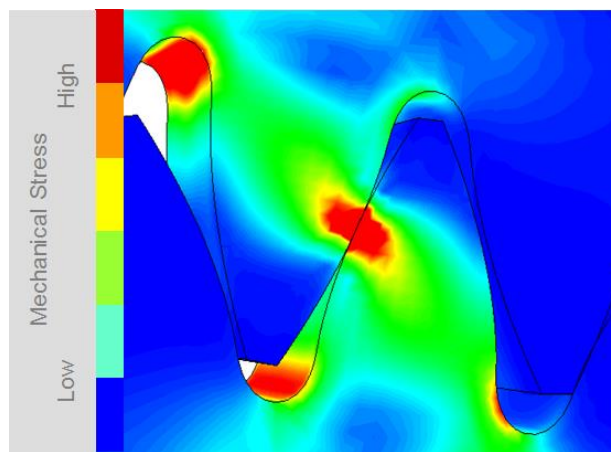

Fig. 12 – Stress on running gears
(Source: WZL-RWTH Aachen)

One popular test method to quantify tooth root fatigue is the Imbalance-Excited Resonance Pulsator—also called the "Pulsator test." Fig. 13 shows the set-up of the test rig.
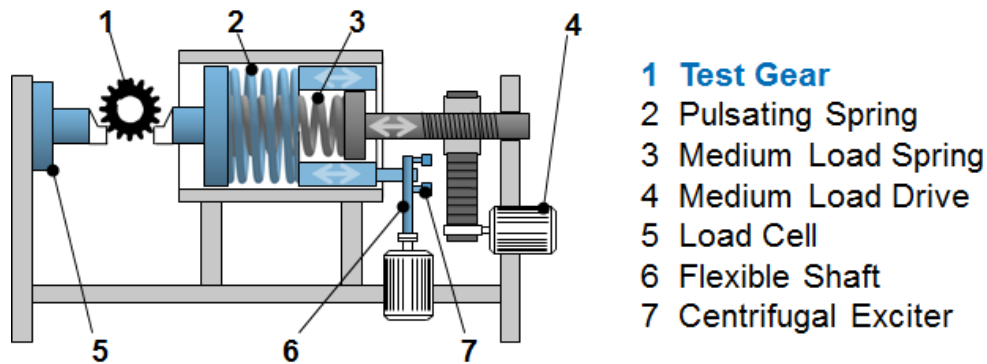

1 Test Gear
2 Pulsating Spring
3 Medium Load Spring
4 Medium Load Drive
5 Load Cell
6 Flexible Shaft
7 Centrifugal Exciter

Fig. 13 – Set-up of Imbalance-Excited Resonance Pulsator (test)
(Source: WZL-RWTH Aachen)

The tested gear is part of a mechanical oscillation system with a sinusoidal load applied. The components are tested with different loads, and as a result, the S/N curve (Wöhler curve) is generated. This curve assigns—for a certain failure probability—the achievable number of load cycles to each load level.

The German drivetrain research association (FVA) has determined S/N-curves in order to compare test gears heat treated with Gas Carb. & Oil Quenching and test gears treated with LPC & HPGQ [14]. These S/N curves were determined by using the Pulsator test. The components were not shot-peened. Fig. 14 shows a comparison of the tooth root bending strength in the range of limited fatigue life at $N = 3 \cdot 10^4$ load cycles for 50% failure probability. Two different materials were tested. For both materials 20MnCr5 and 18CrNiMo7-6 the gears treated with LPC demonstrated higher bending strength than the gas carburized ones. When comparing the gears made of 18CrNiMo7-6 treated with LPC at 940°C with those treated at 1050°C the later ones showed significantly lower strength. This can be explained with the grain growth which occurred during treatment at 1050°C. The test gears were made of a standard grade without micro-alloys, therefore formation of large grains was not avoided.
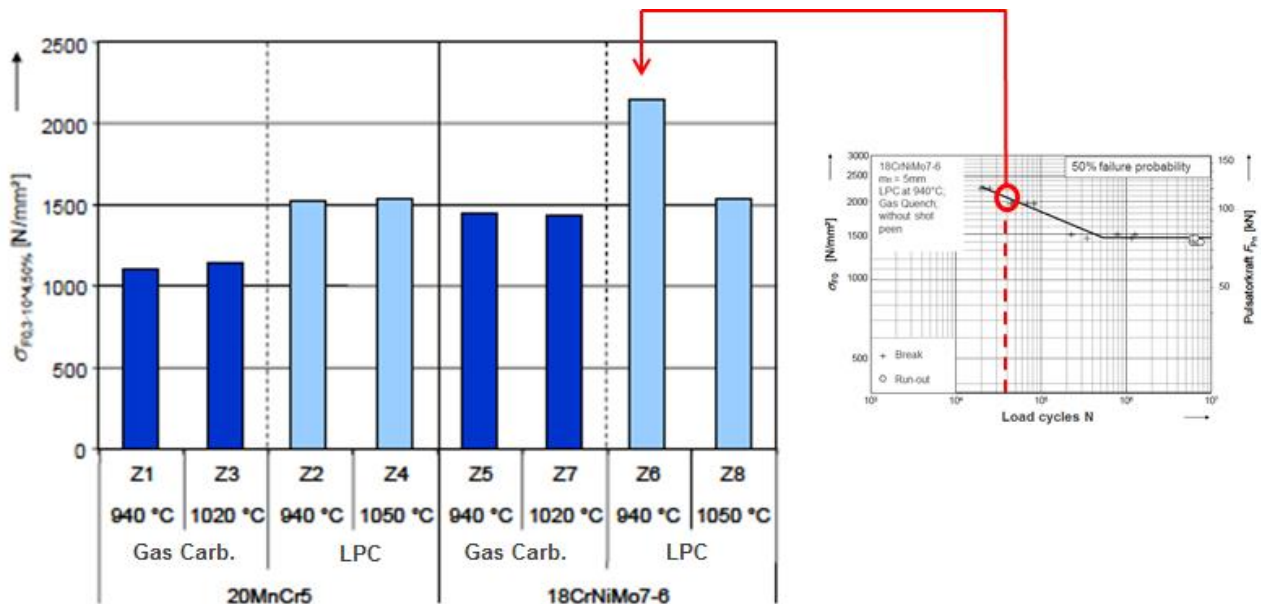

Fig. 14 – Tooth root bending strength in the range of limited fatigue life at N = 3x10⁴ load cycles; 50% failure probability; derived from Pulsator test; comparison of "Gas Carb. & Oil Quench" and "LPC & Gas Quench" and different carb. temperatures; [14]

The nominal bending stress number (endurance limit) is given in Fig. 15. Again, the LPC-treated gears demonstrate higher strength compared to the gas carburized gears.
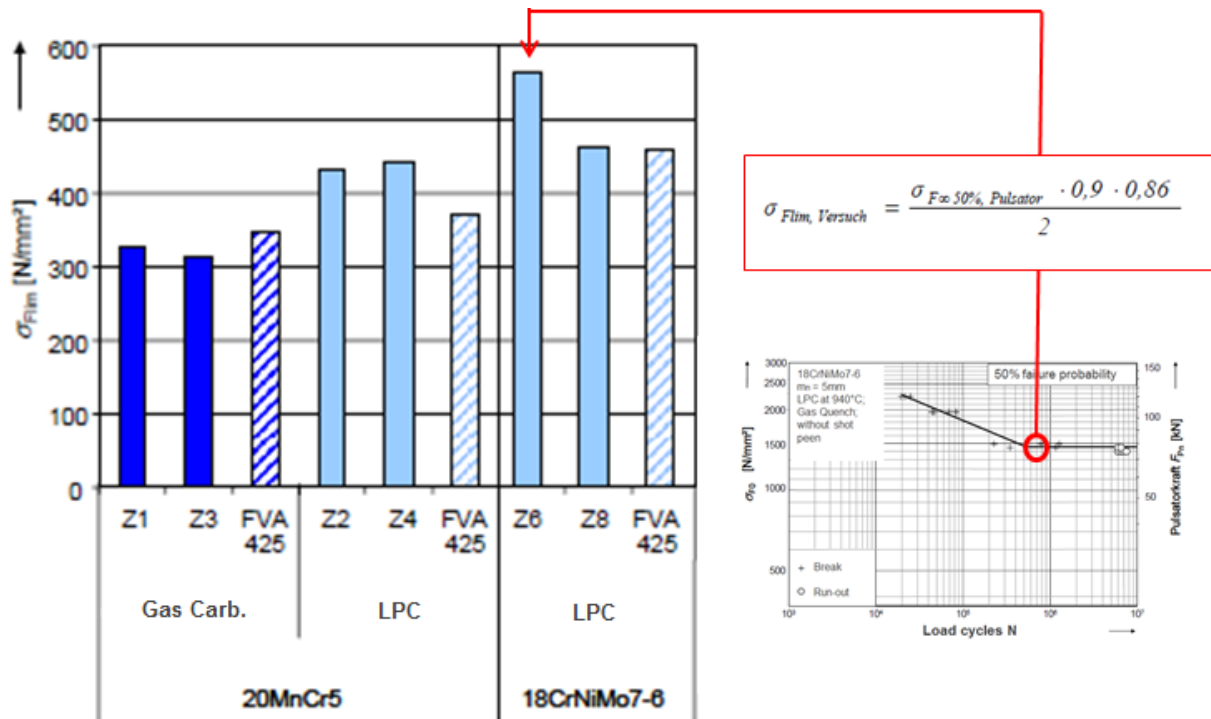

$$\sigma_{Flim,\,Versuch} = \frac{\sigma_{F\infty\,50\%,\,Pulsator}\cdot 0,9\cdot 0,86}{2}$$

Fig. 15 – Nominal bending stress number (endurance limit); derived from Pulsator test; comparison of "Gas Carb. & Oil Quench" and "LPC & Gas Quench" [14]

A summary of the tooth root endurance limit as a function of the carburizing method and the carburizing temperature is given in Fig. 16. Clearly, the LPC-treated gears demonstrate higher tooth root endurance limit (meaning strength against tooth break at the tooth root) compared to gas carburized gears. When analyzing pitting on the tooth flank, the same results were obtained when comparing LPC-treated and gas carburized test gears [14].
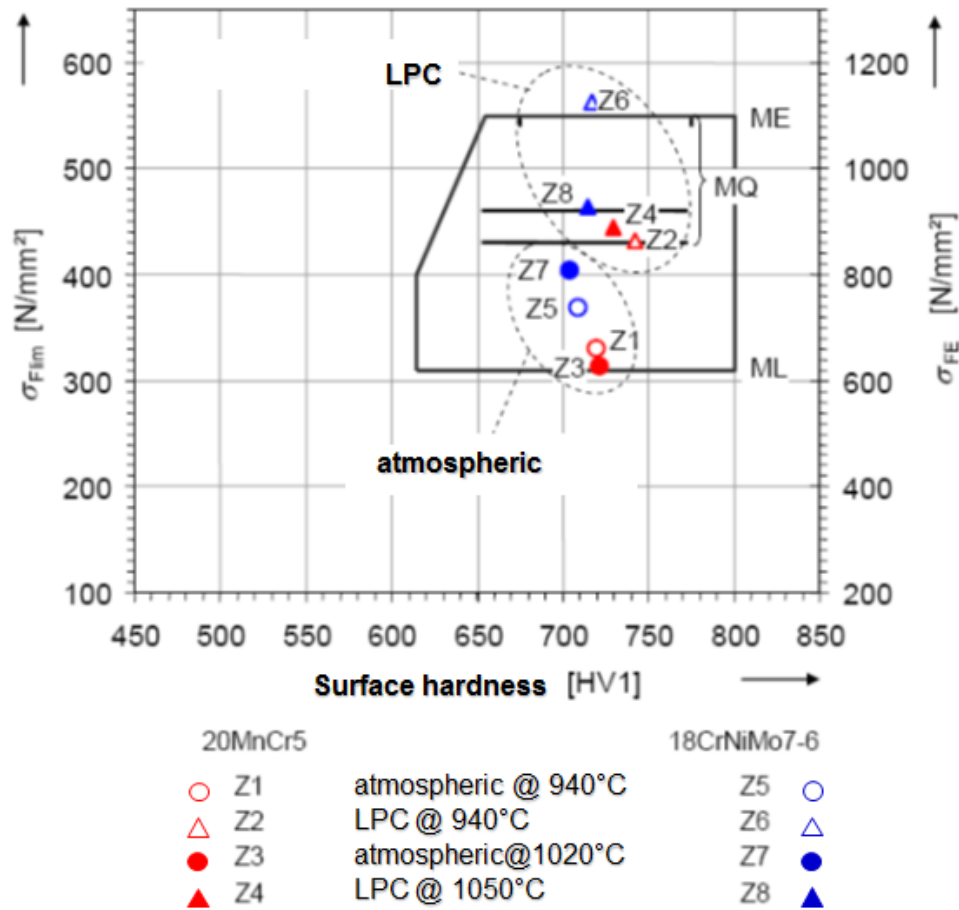
Fig. 16 – Tooth Root Endurance Limit (nominal bending stress number) as a function of the carburizing method and the carburizing temperature [14]

Summary and future works

Improvements in heat treatment technology and improvements of material are key factors to enhance the fatigue resistance for gear components. A clear trend towards

- a restriction of hardenability of the steel, and

- an increase of hardenability of the steel

could be observed over recent years. As a result, the variations in core hardness and case hardening depth (CHD) after heat treatment were significantly reduced. Another important benefit when restricting material hardenability is an improvement of distortion control, which was described in earlier publications.

The application of advanced heat treatment technologies such as Low Pressure Carburizing (LPC) in combination with High Pressure Gas Quenching (HPGQ) offers a lot of benefits. One of them is an enhancement of tooth root bending strength compared to the technology of Gas Carburizing with Oil Quenching.

With the introduction of newly-developed microalloyed case hardening steels, the LPC temperatures can be increased up to 1050°C (1920°F), and even higher. Raising carburizing temperature results in a dramatic reduction of cycle time, and therefore in great savings of production costs and energy.

Bibliography

[1]   Herring, D.: Fundamentals of heat treating: Ideal diameter. In: Industrial heating Sept. 2005, pp. 18–20

[2]   ASTM A255-10(2014), Standard Test Methods for Determining Hardenability of Steel, ASTM International, West Conshohocken, PA, 2014

[3]   Heuer V.: Chapter "Low-Pressure Carburizing". In: ASM handbook Volume 4A, 2013; pp. 581–590

[4]   Heuer V.: Chapter "Gas Quenching". In: ASM handbook Volume 4A, 2013; pp. 222–231

[5]   Heuer, V; Loeser , K; Schmitt, G.; Ritter, K.: Integration of case hardening into the manufacturing line: „One Piece Flow"; AGMA Technical Paper 11FTM23, 2011.
(ISBN 978-1-61481-023-0)

[6]   Heuer, V.; Loeser, K.; Faron, D.R.; Bolton, D.: Low distortion heat treatment of transmission components; AGMA Technical Paper 10FTM04, 2010. (ISBN 978-1-55589-979-0)

[7]   Altena H.: Niederdruckaufkohlung mit Hochdruckgasabschreckung. In: HTM 57 (2002), 4

[8]   Koch, A., Steinke, H., Brinkbäumer, F., Schmitt, G.: Hochtemperatur-Vakuumaufkohlung für große Aufkohlungstiefen an hoch belasteten Rundstahlketten. In: Der Wärmebehandlungsmarkt 4/2008, S. 5–7

[9]   Autorenkollektiv AWT-FA 5; AK4: Die Prozeßregelung beim Gasaufkohlen und Einsatzhärten; Expert Verlag 1997

[10]   Hippenstiel, F. et al: Innovative Einsatzstähle als maßgeschneiderte Werkstofflösung zur Hochtemperaturaufkohlung von Getriebekomponenten; In: HTM 57 (2002), S. 290ff.

[11]   Hippenstiel, F. : Tailored Solutions in Microalloyed Engineering Steels for the Power Transmission Industry. In: Materials Science Forum Vols 539-543 (2007); S. 4131–4136

[12]   Hoch, S.; Kleff, J.; Kellermann, I.; Schulz, M.: Temperature – the key to optimize cost and result in carburizing vehicle driveline parts: Proceedings of the Intern. Conf. on Steels in Cars and Trucks, June 5 to 10, 2005, Wiesbaden pp. 245–255 (ISBN 3-514-00718-7).

[13]   Klenke, K.; Kohlmann, R., Reinhold P., Schweinebraten, W.: Kornwachstumsverhalten des Einsatzstahles 20NiMoCr6-5 (VW4521+Nb) für Getriebeteile beim Hochtemperaturaufkohlen, HTM J. Heat Treatm. Mat. 63 (2008) 5, pp. 265–275

[14]   FVA-Abschlussbericht zum FV-448 Hochtemperaturaufkohlen; authors: Steinbacher, M.; Stenico, A. Heft 800, 2006