Low-Distortion Heat Treatment of Transmission Components

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Management Summary

In many applications the high demands regarding service life of transmission 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.

However, as a side effect, the components get distorted during heat treatment. This distortion has a significant cost impact because distorted components often need to be hard-machined after heat treatment. Therefore the proper control of distortion is an important measure to minimize production costs.

By applying the technology of low-pressure carburizing (LPC) and high-pressure gas quenching (HPGQ), heat treat distortion can be significantly reduced.

HPGQ provides a very uniform heat transfer coefficient. The predictability of movement during quenching is more certain and uniform throughout the load. Further improvements can be achieved by the "dynamic quenching" processes where the quenching severity is varied during the quench sequence by step control of the gas velocity. Proper fixturing is another factor for distortion control. Modern CFC (carbon-reinforced carbon) materials are well suited as fixture material for gas quenching.

This paper presents how LPC and HPGQ processes are successfully applied on internal ring gears for a six-speed automatic transmission. The specific challenge in the heat treat process was to reduce distortion in such a way that subsequent machining operations are entirely eliminated. As a result of extensive development in the quenching process and the use of specialized CFC fixtures, it was possible to meet the design metrological requirements.

The internal ring gears addressed in this report have been in continuous production since 2006. Subsequent testing and monitoring over a two-year period progressively demonstrated that consistent metrology was achieved and quality inspection was reduced accordingly.

Introduction

Proper distortion control has become more important than ever before: To answer the demand for fuel-efficient vehicles, modern transmissions are built much lighter; therefore the components of the transmission exhibit less wall thickness, which makes them more sensitive to distortion. And distorted gear components cause noise in the transmission, may require post-heat treat machining processes and may even create problems during transmission assembly.

By applying the technology of low-pressure carburizing (LPC) and high-pressure gas quenching (HPGQ), heat treat distortion can be significantly reduced. LPC is a case-hardening process performed in a pressure of only a few millibar, using acetylene as the carbon source in most cases. During HPGQ the load is quenched using an inert gas stream instead of a liquid quenching media; typically, nitrogen or helium are used as the quench gas.

With an optimized distortion control, it is possible to simplify the process chain significantly. Figure 1 shows how the process chain can be simplified if the specified geometrical values of the components can be guaranteed after gas quenching.

If the simplified process chain can be applied, then this will result in lower costs per part, lower throughput times and lower energy consumption during production. Since there is no need to dispose any oil after the quench, and cleaning operations after the quench are unneeded, the simplified process chain is much more environmentally friendly as well.

For the internal ring gears addressed in this report, the parts used to be heat treated with an induction hardening process. This process requires a 50-carbon and high-alloy steel grade that is very challenging for machining, or a non-ferritic grade of cast iron that is challenging for casting. The intent was to change from induction hardening to case hardening, and to guarantee a low level of distortion after case hardening to allow for direct assembly into the transmission.

Distortion Mechanisms

The plastic deformation of metallic components during heat treatment is referred to as distortion; distortion occurs if the stress in the material exceeds the yield stress of the material. During case hardening the components are exposed to high temperatures in the range of 880°C to 1,050°C, and the yield stress decreases strongly with increasing temperature of a component. Three different types of stress in the material need to be distinguished:

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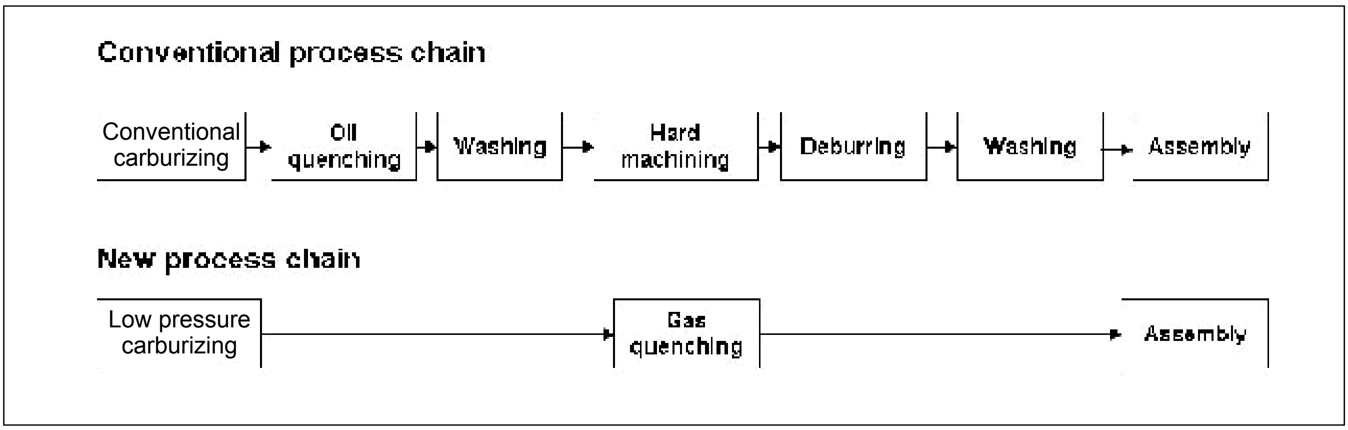

Figure 1—Conventional and new process chain for the manufacturing of gear components.

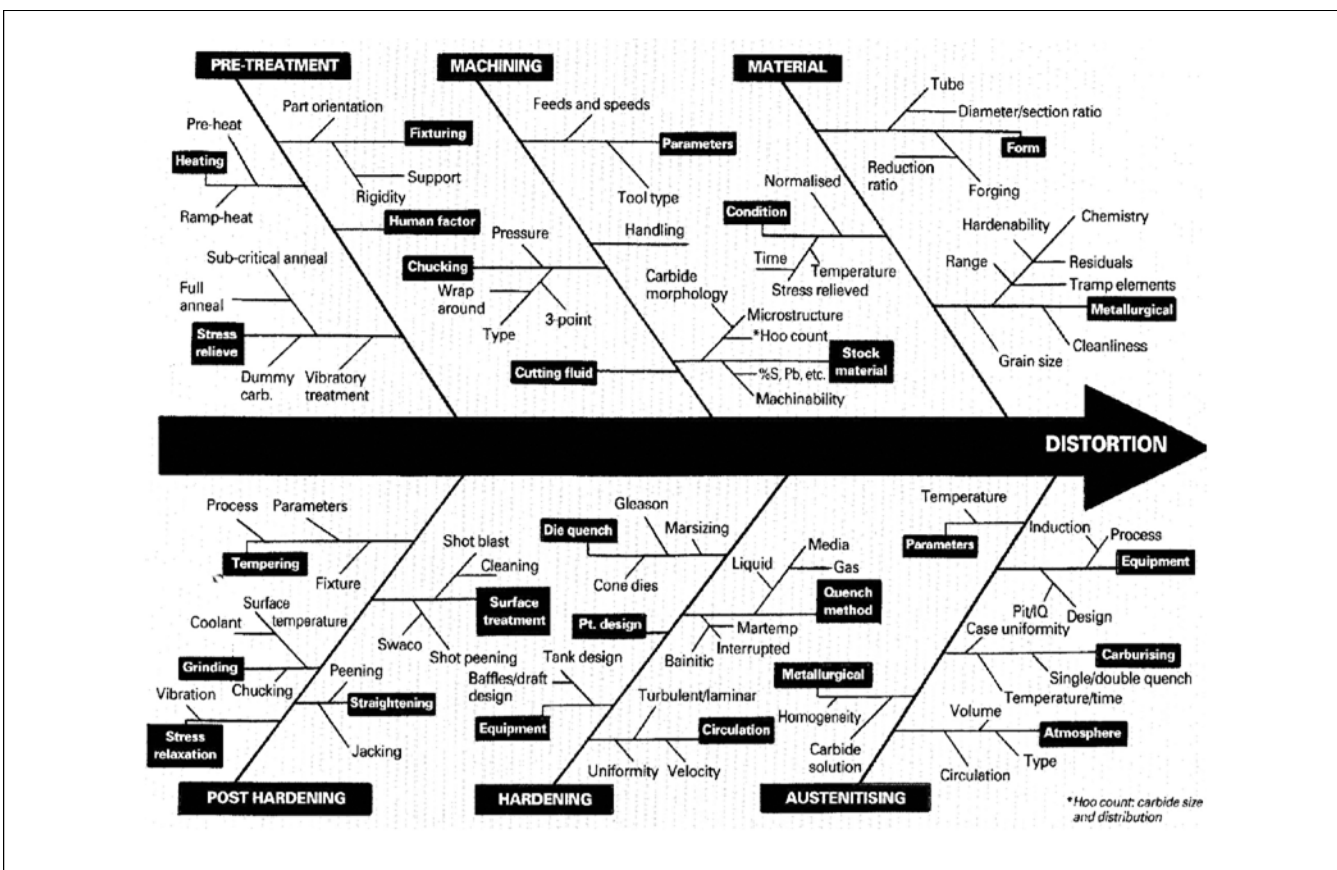

Figure 2—Potential factors influencing distortion of bearing rings (Ref. 2).

- Residual stresses induced before heat treatment by casting, forging, machining, etc. (Ref. 1)
- Thermal stresses caused by the temperature gradient while heating and quenching
- Transformation stresses caused by the transformation from ferrite to austenite during heating, and transformation from austenite to martensite/bainite during quenching

These three types of stresses overlay with each other and add up to the total stress in the component. They are influenced by part geometry, steel grade, casting, forging, machining, etc., and they depend on heat treatment. If the total stress in the component exceeds the yield stress, plastic deformation (distortion) of the component occurs. The chronology and the height of the three types of stresses leading to distortion are dependent on numerous different factors (Fig. 2).

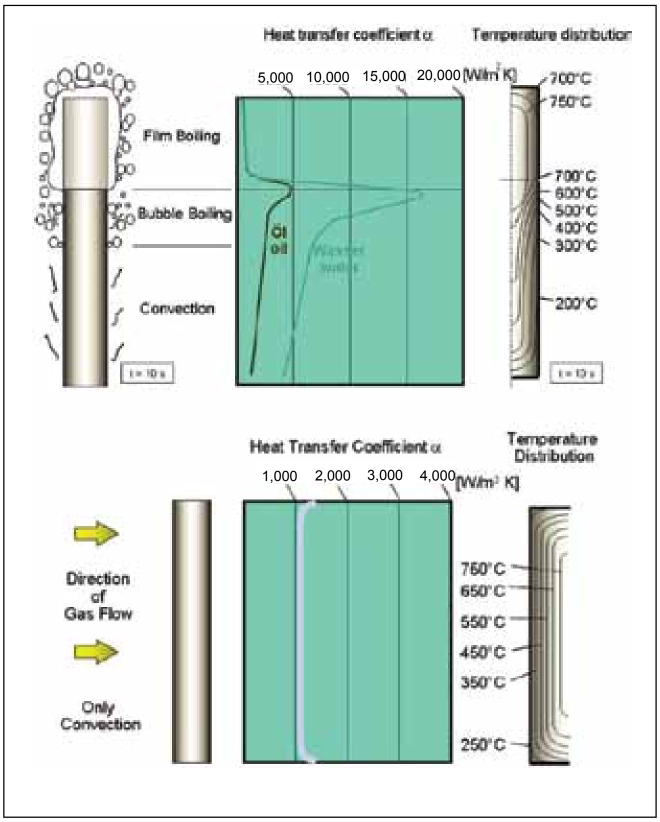

Figure 3—Heat transfer coefficient and temperature distribution in liquid and gas quenching (Ref. 3).

Figure 4—ModulTherm heat treat system with gas quenching chamber.

High-Pressure Gas Quenching (HPGQ)

The technology of HPGQ offers a tremendous potential to reduce heat treat distortions. Conventional quenching—technologies such as oil- or polymer-quenching—exhibits very dissimilar cooling conditions. Three different mechanisms occur during conventional liquid quenching: film boiling, bubble boiling and convection. Resulting from these three mechanisms, the distribution of the local heat transfer coefficients on the surface of the component are very inhomogeneous. These inhomogeneous cooling conditions cause tremendous thermal and transformation stresses in the component and subsequent distortion. During HPGQ only convection takes place, resulting in much more homogeneous cooling conditions (Fig. 3).

Significant reductions of distortion by substituting oil quench with HPGQ have been published (Ref. 9). Another advantage of HPGQ is the capability of adjusting the quench intensity exactly to the needed severity by choosing quench pressure and quench velocity; typical quench pressures range from 2 bar to 20 bar. The gas velocity is controlled by a frequency converter and typical gas velocities range from 2 m/s to 15 m/s, depending on part geometry and steel grade of the component.

Equation 1 describes the heat transfer coefficient as a function of gas velocity, gas density and the type of gas (Ref. 4):

$$\alpha = C w^{0.7} \rho^{0.7} d^{-0.3} \eta^{-0.39} c_p^{0.31} \lambda^{0.69} \qquad (1)$$

Where:

C	Constant factor (depending on quench cell)
W	Gas velocity
ρ	Gas density
d	Diameter of component
η	Viscosity of the gas
c_p	Specific heat capacity of the gas
λ	Thermal conductivity of the gas

Typical gases applied for HPGQ are nitrogen and helium (Ref. 5). To achieve the required core hardness in gears of low-alloyed, case-hardening steels, helium as a quenching medium and a gas pressure of 20 bar are necessary for many applications. The usage of this low-density gas allows quenching with very high gas velocity by using reasonable motor power. In combination with an advanced gas recovery technology and exhibiting a recovery rate > 99.5%, gas quenching is very economic in spite of the helium gas price. The positive experiences with gas quenching have induced gear suppliers to use case-hardening steels with better hardenability, thus being able to quench bigger transmission components as well.

For many applications it is not the absolute height of distortion causing manufacturing problems—it's the spread of distortion. So for many applications the challenge is to optimize the HPGQ in such way that it provides a heat treatment process with very little spread of distortion within a load and, over time, from load to load.

Furnace Equipment and Fixturing for Distortion Control

The design of the gas quenching chamber is of key importance to minimize distortion. The chamber needs to provide a high gas velocity to ensure that the core hardness specification is met, and the chamber needs to provide a very uniform distribution of the gas velocity to minimize the spread of distortion within the load. Intensive numerical flow calculation (CFD studies) and experimental studies with the Institute for Industrial Aerodynamics at Aachen University led to the design of the quenching chamber of the ModulTherm system (Fig. 4; Ref. 6).

Two high-powered gas circulators arranged to left and right of the cylindrical housing accelerate the quenching gas to a high velocity in the chamber; a very homogeneous flow through the charge is reached by means of several flow guides.

The design of the chamber is modular and can be equipped with a gas flow reverse system. The quench chamber is suitable for standard gas quenching processes with constant gas pressure and gas velocity, as well as for new quenching processes such as dynamic quenching.

As in the case of liquid quenching, proper fixtures and optimized loading of parts is important for gas quenching. Alloy fixtures are widely used in heat treatment; however after long-term service the fixtures tend to deform due to high temperature deformation that has a negative effect on the distortion of the loaded parts. Moreover, due to the pick-up of carbon and subsequent formation of carbides, the fixtures undergo dimensional growth that create further problems during handling in automated, external-transportation devices.

As an alternative, carbon composite materials—e.g., CFC—were introduced for use as fixtures in heat treating applications. Low-pressure carburizing furnaces with high-pressure gas quenching are perfectly suited for the use of CFC fixtures (Fig. 5). With the usage of walking beam transportation, any wear and overstressing of the fixtures are avoided. The use of oxygen-free hydrocarbons in a vacuum environment and the inert quenching gases during the quenching process avoid any surface reactions with the fixtures. In this service environment, one can take full advantage of the excellent material properties of CFC, which has very high deformation resistance at high temperatures, low thermal expansion coefficient, and very low specific weight. Fixtures from CFC are designed to carry more parts while exhibiting less gross weight and thereby increasing productivity and reducing energy costs. The major advantage, however, is that CFC fixtures do not show deformation during the heat treatment process, thereby assuring optimum

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Figure 5—Load of internal ring gears on CFC fixturing.

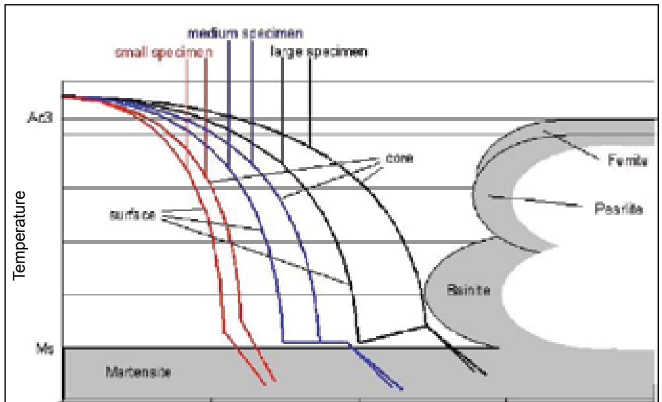

Figure 6—Schematic illustration of dynamic quenching for specimen of different sizes.

Figure 7—Geometrical inspection of an output internal gear with a CNC analytical gear checker.

positioning of the parts. This has a significant, positive effect on part distortion.

Dynamic Quenching

To achieve optimum quenching results with respect to microstructure, hardness and distortion, the gas quenching parameters need to be well adjusted.

To further reduce distortion, a quenching process has been developed where the quenching parameters' gas pressure and/or gas flow velocity are varied stepwise during quenching (Fig. 6).

The process of dynamic quenching is typically divided into three steps (Ref. 7):

1. High quenching severity until a certain part temperature is reached
2. Quenching severity is reduced for a set time to allow for temperature equalization in the part
3. Quenching severity is increased again until the end of the quenching process. The control system in the quenching chamber allows for control of the dif ferent quenching steps of dynamic quenching in a very accurate way and with good reproducibility.
4. Optimum results are achieved when using helium. The light quenching gas helium can be decelerated and accelerated very precisely for optimum distortion control.

Distortion Study

An intensive process optimization program was started before the start of production of the six-speed automatic transmission; the specific challenge was to optimize distortion control of the internal ring gears. The goal was to eliminate hard machining completely on these components, thus simplifying the process chain as postulated in Figure 1. Furnace supplier and transmission manufacturer worked in close cooperation and successfully implemented a serial process for the start of production in 2006. The process consists of LPC using acetylene as the carburizing source and HPGQ using helium as quench medium. Prior to carburizing, the parts are heated under an atmosphere of 1, 2-bar nitrogen. This "convective heating" is applied to achieve uniform temperature distribution inside the load while heating up. Once the carburizing temperature is reached, the pressure is lowered to a few millibars and carburizing is initiated. The application of HPGQ with dynamic quenching and the use of CFC fixtures made subsequent machining operations unnecessary. The findings were published by the authors of this paper in 2006 (Ref. 8).

Initially all internal ring gears from each load were checked for excessive distortion with a "roll checker"—an automated measurement system utilizing a rolling master held by a pivoting yoke. The yoke enables the roll master spindle to move in the lead and taper directions as the rolling master rotates in tight mesh with the test component. Separate transducers located in the gimble head monitor lead and taper travel.

To become more cost-efficient, the transmission manufacturer wanted to abandon this 100% roll checker inspec-

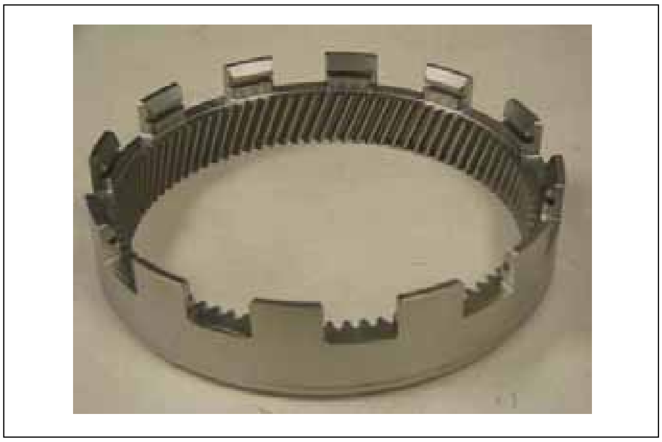

Figure 8—Input internal gear (*d* = 139 mm, 89 internal teeth).

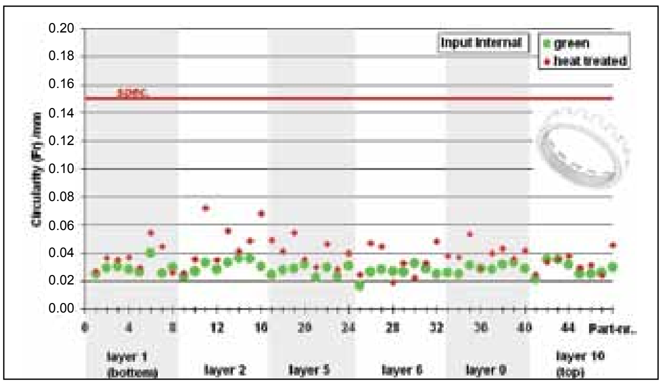

Figure 9—Circularity of input internal gears before and after heat treat (LPC and HPGQ with dynamic quenching); specimen maximum after heat treat—150 μm.

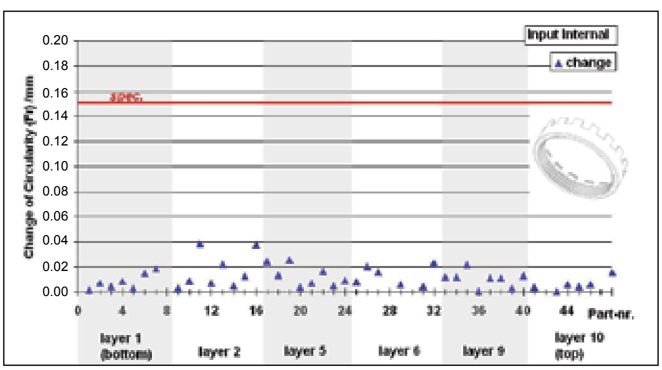

Figure 10—Change of circularity of input internal gears during heat treat (LPC and HPGQ with dynamic quenching); specimen maximum after heat treat—150 μm.

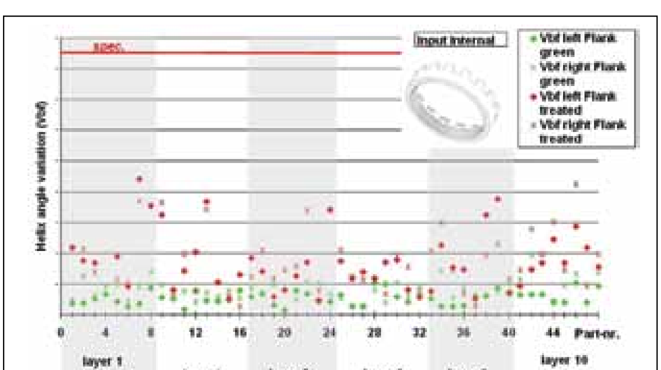

Figure 11—Helix angle variation of input internal gears before and after heat treat (LPC and HPGQ with dynamic quenching).

tion of all parts and change to a spot-wise control of distortion. The goal was to inspect only two gears per load. Therefore it was necessary to further reduce the amount of distortion, and the quenching process was optimized again in 2008. Distortion studies were performed accordingly on the three internal gears—i.e., reaction output and input of the internal gears.

For each part, the current standard production process was used and complete load sizes were treated. Forty eight pre-measured parts were equally distributed into different layers of each load. Additionally, to cover all "extreme" positions in the load, it was made sure that parts from all eight corners and parts from the middle of the load were geometrically inspected. All measurements were performed with a CNC analytical gear checker. Figure 7 shows the inspection of an output internal gear with the probe of the gear checker moving along one tooth of the gear. Four teeth are inspected for each gear and both left flank and right flank are examined per tooth.

The production process for all three gears includes convection heating for a fast and uniform heating up of all parts. After being properly heated, the parts are carburized at 900°C by using acetylene. The temperature is reduced to an intermediate temperature and then the parts are quenched with helium using an optimized dynamic quenching process.

Input internal gears. The components have an outer diameter of 139 mm, 89 internal teeth and are made of 5130 material (Fig. 8).

The case-hardening depth (CHD) after heat treat is specified as 0.3–0.6 mm and surface hardness is specified as 79–83 HRA. The geometry after heat treat is specified with a maximum circularity of 150 mm.

Figure 9 shows the circularity of the 48 measured parts before and after heat treatment. The change of circularity during heat treat is shown in Figure 10. When evaluating and comparing heat treat distortion, the change of geometry from the green to the treated component should be considered.

Figure 11 shows the variation of the helix angle per part for the left and the right flank. Four teeth were measured per part, and the variation *Vbf* represents the difference between the maximum helix angle and the minimum helix angle measured on the four teeth per one gear.

As shown in Figures 9–11, the achieved level of distortion is very small; maximum change in circularity amounts to 38 µm and the average change in circularity is as low as

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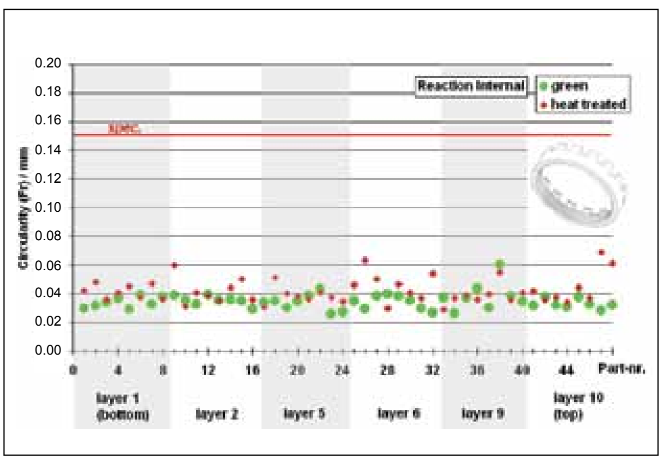

Figure 12—Circularity of reaction internal gears before and after heat treat (LPC and HPGQ with dynamic quenching); specimen maximum after heat treat—150 µm.

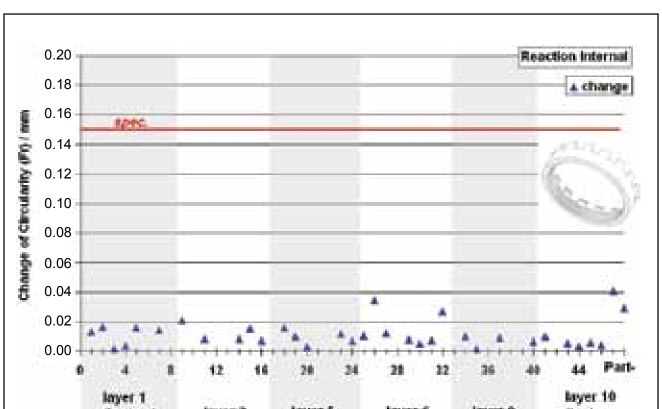

Figure 13—Change of circularity of reaction internal gears during heat treat (LPC and HPGQ with dynamic quenching); spec. maximum after heat treat: 150 µm.

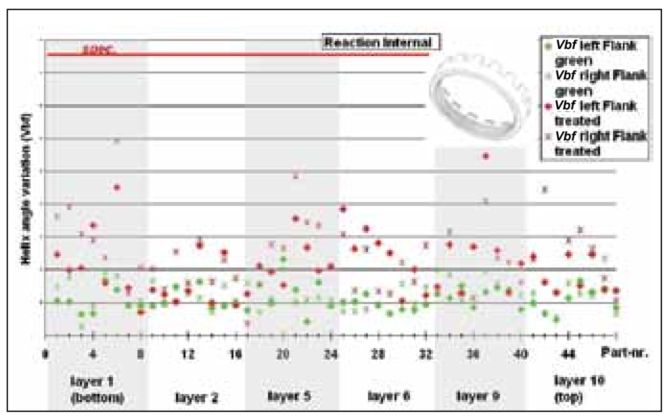

Figure 14—Helix angle variation of reaction internal gears before and after heat treat (LPC and HPGQ with dynamic quenching).

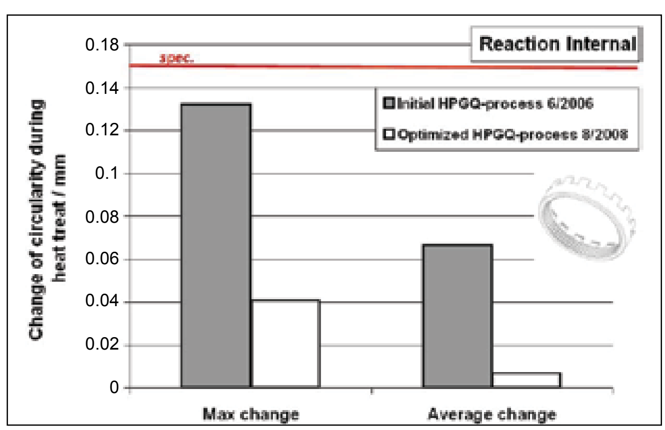

Figure 15—Maximum and average change of circularity during heat treatment in a load of reaction internal gears; comparison of initial production process from 2006 and the optimized production process used since 2008; specimen maximum after heat treat—150 µm.

10 μm; all circularity values after heat treat are well below the specified maximum of 150 μm; helix angle variation after heat treat is well below the specified maximum as shown in Figure 11; average change during heat treat in helix angle variation is 12 μm for the left flank and 9 μm for the right flank.

Reaction internal gears. The reaction internal gears have an outer diameter of 152 mm, 103 internal teeth and are made of 5130 material as well. Specification of the parts after heat treat is identical to the input internal gears.

The circularity of the 48 measured pieces before and after heat treatment can be found in Figure 12; Figure 13 shows the change of circularity during heat treat.

The helix angle variation (*Vbf*) for each part is shown in Figure 14; as shown in Figures 12–14 the achieved level of distortion is also very small for the reaction internal gears; maximum change in circularity amounts to 41 μm and average change in circularity only 7 μm; all circularity values after heat treat are well below the specified maximum of 150 μm; the helix angle variation after LPC and HPGQ is below

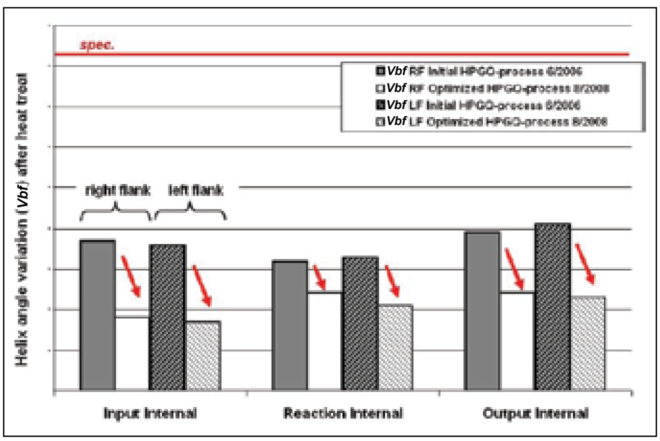

Figure 16—Helix angle variation after heat treatment averaged per load for input reaction and output internal gears; comparison of initial production process from 2006 and the optimized production process since 2008.

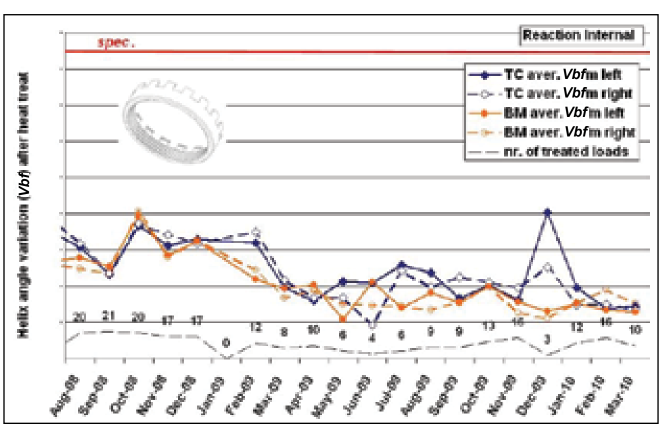

Figure 17—Reaction internal gears: helix angle variation after heat treat averaged per month of production: (TC = sample from top corner of the load; BM = sample from bottom middle of the load; the number of inspected loads is indicated per each month; the total number of inspected loads from 2008 until 2010 was 229 loads; no production in 2009).

the specified maximum as well; the average change during heat treat in helix angle variation is 10 μm for the left flank and 11 μm for the right flank.

Output internal gears. The components have an outer diameter of 139 μm, 99 internal teeth and are made of 5130 material (Fig. 7). The level of distortion achieved on these gears is slightly higher compared to the values achieved for the input and reaction internal gears; maximum change in circularity amounts to 81 μm and average change in circularity is 28 μm, meaning that all circularity values after heat treat are well below the specified maximum of 150 μm. The helix angle variation after LPC and HPGQ is within specification as well; average change during heat treat in helix angle variation is 9 μm for the left flank and 10 μm for the right flank.

Comparison of the Initial and the Optimized HPGQ Process

The data presented in the previous section represents a significant reduction of the already-low distortion values from 2006; the dynamic quench process was optimized in 2008. To do so the hold temperature was manipulated in the vicinity of the estimated martensite start (MS) temperature by an adjustment of the gas speed and timing for all three steps of the dynamic quench process. This process optimization, in combination with the very stable manufacturing process chain before heat treat, led to the significant improvements demonstrated in Figures 15–16.

Figure 15 shows a comparison of two loads of reaction internal gears; one load was treated in 2006 with the initial HPGQ process (Ref. 8), the other with the optimized HPGQ process. The average change of circularity during heat treat was reduced from 67 to 7 μm and the biggest change of circularity inside the load was reduced from 132 to 41 μm.

The helix angle variations after heat treat from six different loads are presented in Figure 16. One load of each type of internal gears was treated in 2006 with the initial HPGQ process, and one load of each type treated with the optimized HPGQ process. The helix angle variations were significantly reduced for both for the right and left flanks. As discussed earlier in this paper, the residual stresses inside the components can contribute to distortion, which means that the level of residual stress inside these gears before heat treat must be very low to allow such a low level of distortion after heat treatment.

Distortion Monitoring in Serial Production

Serial production of the transmission started in 2006. Initially all internal ring gears from each load were checked for excessive distortion with a roll checker. As distortion proved to be very consistent after introduction of the optimized process in 2008, the transmission manufacturer decided to abandon the 100% inspection of all parts. Since 2008, only two gears per load are being measured with a CNC analytical gear checker. One part from the top corner and one part from the bottom-middle are being inspected in each load; these two positions were chosen to cover the "extreme" positions in the load.

Results from distortion monitoring since introduction of the optimized process in 2008 until today are presented in Figure 17; the diagram shows the helix angle variation after heat treat (*Vbf*) averaged per month of production. TC represents the sample from the top corner of the load and BM represents the sample from the bottom-middle of the load. Additionally, the number of inspected loads per month is indicated in the diagram; total number of inspected loads from 2008–2010 was 229 loads.

Figure 17 demonstrates that the distortion values in serial production are very stable. This was achieved with the help of the optimized LPC and HPGQ process, in combination with the stable manufacturing process chain of the components.

Necessary Steps for Low-Distortion Heat Treatment

The necessary steps that need to be accomplished to provide low distortion values are given in Figure 18.

The design of the gas quenching cell is of key importance to minimize distortion. The chamber needs to provide a very uniform distribution of the gas velocity to minimize the spread of distortion within the load. Another important factor is proper fixturing; modern CFC materials (carbon reinforced carbon) are well-suited as fixture material for gas quenching.

Further improvements can be achieved by optimized LPC processes using convective heating for homogeneous temperature distribution and by application of dynamic quenching processes where the quenching severity is varied during the quench sequence by step control of the gas velocity. However, if the components inhibit high residual stress, it is then impossible to achieve low distortion values during heat treat. Therefore an optimized and stable manufacturing process chain including melting, casting, cutting, soft machining, etc., is mandatory to create low levels of residual stress in the components before heat treating.

Summary

LPC and HPGQ processes were successfully applied on internal ring gears for a six-speed automatic transmission. Helium was chosen as quench gas. Distortion studies were conducted to analyze the geometrical stability of the input, reaction and output internal gears during heat treat. In each case 48 pre-measured parts were blended into a full production load. For reaction internal gears, the maximum change of circularity during heat treat was 41 μm and the average change of circularity was as low as 7 μm. The average change during heat treat in helix angle variation was 10 μm for the left flank and 11 μm for the right flank. All values after heat treat are well below the specified maximum. Measurements of input and output internal gears showed similar results, with all gears being well within specification. The level of distortion stays at such a low level that subsequent machining operations are entirely eliminated. This led to enormous cost savings for the transmission manufacturer.

Production of the gears started in 2006; results from continuous distortion monitoring during production prove that the distortion of the LPC and HPGQ process is very stable. Therefore in 2008 it was decided to reduce the quality inspection drastically, which resulted in significant cost savings.

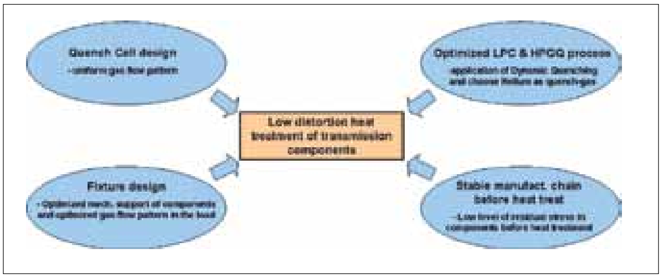

Figure 18—Necessary steps for low-distortion heat treatment with LPC and HPGQ.

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