LEAN HEAT TREATMENT FOR DISTORTION CONTROL
Proper control of heat treat distortion is of key importance to reduce production costs in gear manufacturing.

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Controlling distortion is of key importance during the case hardening process for the production of gear components. By effective control of distortion and the variation of distortion, significant costs in post-heat treatment machining processes can be avoided. In some cases, it is even possible to eliminate all post-machining operations. In other cases, it may be possible to avoid the press-quenching of individual components, resulting in huge cost-benefits.

New vacuum furnace designs allow the treatment of small batches in a single layer of parts (“2D-treatment”), which allows for easy automated loading and unloading of the fixture-trays. By using the smallbatch concept, a continuous flow of parts can be established (“One Piece Flow”). There is no need to wait until enough parts are collected to build a large batch with multiple layers (“3D-treatment”). This compact furnace unit can be implemented into the heart of the production chain and provides heat-treatment processes that can be fully synchronized with the green- and hard-machining operations.

When performing case hardening, the components are Low Pressure Carburized (LPC) at high temperatures followed by gas quenching. The treatment in single layers offers an optimum in quality regarding:

- Temperature homogeneity.
- Quench homogeneity.
- Distortion control.

The paper shows new results of distortion control from several studies on different gear components. In addition, latest results of distortion control from serial gear production is presented.

1. INTRODUCTION

With the introduction of E-mobility, proper distortion control has become even more important than in previous days. Distorted gear components cause noise in the transmission. Especially battery-operated electric vehicles (BEVs) and all other electrified vehicles (including hybrids) will require a low noise transmission with high precision components.

Distortion has a strong cost-impact, since distorted components need to be hard-machined after heat treatment.

Better control of distortion means:

- Less cycle time per part in hard-machining.
- Less hard-machining capacity needed.

Less tooling cost for hard machining.

For some applications, hard machining can be completely eliminated with an excellent control of distortion.

The paper shows how distortion control is improved when applying lean and tailored Low Pressure Carburizing (LPC) – processes.

2. DISTORTION MECHANISMS AND HIGH PRESSURE GAS QUENCHING (HPGQ)

The relevant mechanisms that cause distortion of components during heat treatment have been described extensively in literature [3]. Three different types of stress in the material contribute to distortion: residual stresses, thermal stresses and transformation stresses [7].

![Figure 1: Potential factors influencing distortion [14.]](image-url)

These stresses are influenced by part-geometry, steel-grade, casting, forging, machining, etc. and they depend on the heat treatment. If the total stress in the component exceeds the yield stress, then distortion of the component takes place. Walton [14] published the numerous potential factors that are influencing distortion in more detail, see Figure 1.

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 that is performed in a pressure of only a few millibars 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. Usually, nitrogen...
HPGQ offers a tremendous potential to reduce heat-treat distortion. Conventional quenching technologies such as oil- or polymer-quenching exhibit inhomogeneous 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 is very inhomogeneous. These inhomogeneous cooling conditions cause tremendous thermal and transformation stresses in the component and subsequently distortion. During HPGQ, only convection takes place, which results in much more homogeneous cooling-conditions [5,7,13].

Significant reductions of distortion by substituting oil-quench with HPGQ have been published [1]. Another advantage of HPGQ is the possibility to adjust the quench intensity exactly to the needed severity by choosing quench pressure and quench velocity. Typical quench pressures range from 2 bars to 20 bars. The gas velocity is controlled by a frequency converter. Typical gas velocities range from 2 m/s to 20 m/s depending on the part geometry and the steel grade of the component. Figure 2 shows a typical industrial system for the HPGQ process. The batches for such systems consist of several layers of production parts resulting in so called “3D-treatment.”

![Figure 2: High Pressure Gas Quenching (HPGQ) chamber of a heat treatment system for 3D-treatment.](image)

3. LEAN HEAT TREATMENT

Today’s production philosophy for gear components usually relies on the traditional separation between soft machining, heat treatment and hard machining. Heat treatment is performed in a central hardening shop. There is no continuous flow of production parts between the different operations such as soft machining, heat treatment, shot peening, and hard machining. Instead the parts are collected into batches and then moved from operation to operation. So, large numbers of production parts are stored in buffers or are in transit between the different operations.

In order to establish a more effective and economic production of gear components, the goal is to move away from batch type logistics and move toward a “One Piece Flow” of production, see Figure 3. The goal is to move single parts from operation to operation instead of moving batches of parts. This One Piece Flow production system (OPF) would realize a continuous flow of production parts and would avoid huge efforts for storage and transportation of parts between operations [2,12]. If such a total integration of all operations can be established, then this will offer new possibilities for automation, which again leads to a reduction of costs. Additionally, a higher level of automation will result in a reduction of defects in quality.

Figure 4 shows a new synchronized heat-treatment module for “One Piece Flow” production which was recently established in industrial production. This heat-treatment module allows for total integration into the manufacturing line creating a synchronized production flow with gear machining.

Following the philosophy of “One Piece Flow” the parts are:

- Taken one-by-one from the soft machining unit.
- Heat-treated in time with the cycle time of soft machining.
Passed down one-by-one to the hard machining unit.

Although the parts are not treated individually but treated in trays, the parts are individually loaded to the heat-treat unit and individually unloaded from it. So the continuous flow of single parts is established.

In comparison to treatment of big batches in multiple layers (3D-treatment), the single layer treatment (2D-treatment) provides:

- Homogenous and rapid heating of the components.
- Homogenous and rapid carburizing of the components.
- Homogenous and precisely controlled gas quenching.

All the variations from layer to layer are eliminated, which leads to reductions in distortion-variation within the load. The concept and the technology of “One Piece Flow” heat treatment have been published earlier in more detail by the authors [6,7].

4. DISTORTION STUDIES – COMPARISON BETWEEN 3D-TREATMENT AND 2D-TREATMENT

4.1 FINAL DRIVE RING GEARs

Final Drive Ring gears from a 6-speed automatic transmission are being produced since 2006 by applying LPC and HPGQ. The parts are treated in big batches with multiple layers (3D-treatment). A distortion study was initiated to quantify the possible improvement in distortion-control when switching from 3D-treatment to 2D-treatment. The Final Drive rings gears have an outer diameter of 226 mm, a height of 32 mm, a weight of 4.2 kg, 59 external teeth, and are made 4121M-material. The case hardening depth CHD after heat treat is specified as 0.7...1.1 mm, core hardness as >28 HRC and surface hardness is specified as 64...69 HR45N.

Before the distortion data was collected, it was made sure that the metallurgical quality in terms of hardness profile, microstructure and core hardness was identical for both treatments. In this study, the geometrical change during heat treatment was compared between today’s multiple layer production process (3D-treatment) at 965°C and the new single layer process (2D-treatment) at 995°C, see Figure 5.

Figure 6 shows the change of flatness during heat treatment. With 3D-treatment the average change is 55 microns and with 2D-treatment, the change is 42 microns, which means a reduction by 24 percent.

Figure 7 shows the change of roundness during heat treatment. With 3D-treatment the average change is 42 microns, and with 2D-treatment, the change is 21 microns, which means a reduction by 50 percent.

Summing up, despite the fact that carburizing with 2D-treatment was performed at 995°C and with 3D-treatment was performed at 965°C, the control of distortion was significantly improved with 2D-treatment.

When changing production from 3D-treatment to 2D-treatment, this will result in huge cost savings for the subsequent grinding process-step.

4.2 REACTION INTERNAL GEARs

4.2.1 REACTION INTERNAL GEARs TYPE A

In an earlier study, the improvement in distortion-control was quantified when switching from 3D- to 2D- treatment for a Reaction Internal gear [7,9]. This Reaction Internal gear from a 6-speed automatic transmission has an outer diameter of 167 mm, 98 internal teeth, and is made of 5130 material, see Figure 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.

Figure 9 shows the load set-up for 3D-treatment and 2D-treatment. All measurements were performed with a CNC analytical gear-checker. Four teeth were inspected for each gear, and both left flank and right flank were examined per tooth.
In this study, it was shown that the standard deviation of helix angle variation $V_{bf}$ for the left flank was reduced by 30 percent down to 7 microns when switching from 3D- to 2D-treatment. For the right flank, the average of helix angle variation was reduced by 30 percent, and the standard deviation of $V_{bf}$ was reduced by 45 percent, see Figure 10. The lower amount of helix angle variation of the parts from single layer treatment indicates that they are flatter after heat treatment compared to the ones from multiple layer treatment.

When comparing the single layer treatment at 900°C with 1,050°C, no increase in $V_{bf}$ was observed. This is certainly remarkable. A standard 5130 steel grade without microalloying for grain size control was used for all tests. Although significant grain growth was detected after treatment at 1,050°C, this did not lead to increased distortion.

4.2.2 REACTION INTERNAL GEARS TYPE B

A second type of Reaction Internal gears was studied. Again, the improvement in distortion control was quantified when switching from 3D to 2D-treatment. This “Reaction Internal gear Type B” has an outer diameter of 152 mm, 103 internal teeth, and is made of 5130 material. The case hardening depth after heat treat is specified as 0.3...0.5 mm, core hardness as > 25 HRC, and surface hardness is specified as 64...69 HR45N.

Before the distortion-data was collected, it was made sure that the metallurgical quality in terms of hardness profile, microstructure, and core hardness was identical for both treatments. In this study, the geometrical change during heat treatment was compared between today’s multiple layer production process (3D-treatment) at 900°C and the new single layer process (2D-treatment) at 980°C. For 3D-treatment, 192 parts are treated in one load, and for 2D-treatment, 8 parts are treated in one load. See Figure 11.

In this distortion study, 181 parts from 3D-treatment were measured and 160 parts from 2D-treatment (taken from 20 furnace-runs) were measured with a CNC analytical gear-checker.

Figure 12 shows the change of circularity during heat treatment. With 3D-treatment, the average change is 19 microns, and with 2D-treatment, the average change is 7 microns, which means a reduction by 63 percent.

Figure 13 shows the circularity after heat treatment, which means the absolute values after heat treatment. With 3D-treatment, the average circularity is 48 microns, and with 2D-treatment, the change is 32 microns, which means a reduction by 33 percent.

When changing production from 3D-treatment to 2D-treatment, this improvement in control of distortion will result in significant cost savings for the subsequent grinding process-step.

4.3 INPUT SHAFTS

The distortion of input shafts was analyzed after 2D-treatment, see Figure 14. The Input shaft is made of 16MnCr5 material, has a mass of ca. 0.7kg and is treated with a load-size of 30 shafts per tray. The case hardening depth CHD after heat treat is specified as 0.5...0.8 mm, surface hardness is specified as 690...790HV and core hardness is specified as 340...480HV.

Two main parameters were analyzed for distortion: axial runout and concentricity. Figure 15 shows the positions for the measurements.

The carburizing temperature was varied from 960°C to 1,050°C. Two different ways of part orientation in the CFC-fixture were tested: “hanging” and “standing,” see Figure 16. Figure 17 shows the concentricity of the shafts for different test conditions.

However, for the application of these components, the axial run-
When changing production from 3D-treatment to 2D-treatment, the improvement in control of distortion will result in significant cost savings for the subsequent grinding process-step.

Figure 12: Change of circularity during LPC-treatment of “Reaction Internal gear Type B”; comparison between 3D-treatment and 2D-treatment.

Figure 13: Circularity of “Reaction Internal ring gear Type B” after LPC-heat treatment (absolute values after HT); comparison between 3D-treatment and 2D-treatment.

Figure 14: Input shaft made of 16MnCr (ca. 0.7kg per shaft).

Figure 15: Positions for measurement of axial runout and concentricity on the Input shaft.

Figure 16: Part orientation of the Input shafts during treatment: “hanging” (left) and “standing” (right).

Figure 17: Concentricity of input shafts after LPC-process under different test conditions in 2D-treatment.
out is more important than the concentricity.

Figure 18 shows the values for maximum axial runout after treatment, the average change of axial runout, and the standard deviation of the change of axial runout. Clearly the part orientation “standing” leads to much better results. When loading the shafts “standing” into the tray, the specification of axial runout after heat treatment (40 microns) was met successfully for all three analyzed carb. temperatures.

4.4 SMALL PLANETARY GEARS AND SLIDING SLEEVES FOR HEAVY TRUCK TRANSMISSION

In an earlier study, Schueler et. al. analyzed the distortion of small planetary gears and sliding sleeves for heavy truck transmissions [11]. All parts were made of ZF7B-material, which is a modified 20MnCr5. Figure 19 shows the components.

For the small planetary gears, conventional atmospheric gas carburizing with oil quenching was compared with Low Pressure Carburizing (LPC) with High Pressure Gas Quenching (HPGQ) applying a 2D-treatment.

For sliding sleeves, conventional atmospheric gas carburizing with press quenching was compared with LPC with HPGQ applying a 2D-treatment.

For the planetary gears, significant less scattering of distortion was observed for the HPGQ with 2D-treatment compared to the conventional process, see Figure 20.

These results are very stable even after carburizing at 1,050°C and were confirmed by two additional batches with same heat-treatment parameters, see Figure 20 right.

Sliding sleeves are distortion critical parts. Therefore, they are often case hardened and press quenched as a standard process.

In the study from Schueler et. al. at first sliding sleeves made of cold formed blanks were analyzed. The measured distortion after HPGQ was huge with large scattering of the results. This can be explained by the high amount of residual stress after cold forming. When press quenching, the geometry is forced into the wanted shape despite the high amount of residual stress.

In a second study, the blanks for the sliding sleeves were hot formed with a later F/P-annealing before soft machining, which reduces the residual stress from prior steps to a minimum. With these blanks, the observed level of distortion after HPGQ with 2D-treatment was equal to the level obtained from press quenching, see Figure 21.

Therefore, producing sliding sleeves with the 2D-treatment concept that fit the requirement might be possible if the dimensions of soft machining are adjusted with respect to the distortion behavior after heat treatment [11].

5. SUMMARY

Proper control of heat-treat distortion is of key importance to reduce production costs in gear manufacturing.

The technology of Low Pressure Carburizing (LPC) combined with High Pressure Gas Quenching (HPGQ) offers the potential to reduce the amount of distortion compared to conventional case-hardening technologies. The amount of distortion can be further reduced when switching from multiple layer LPC-treatment (3D-treatment) to single layer LPC-treatment (2D-treatment).

This was demonstrated in several studies on transmission compo-
ments. For a Final Drive Ring gear from a 6-speed automatic transmission, the average change of flatness during heat treatment was reduced by 24 percent when changing from 3D-treatment to 2D-treatment. The average change of roundness was reduced by 50 percent. This improvement in distortion control will result in significant cost savings for subsequent hard turning and grinding process steps.

Further practical examples for improved distortion control on internal gears, Input shafts, sliding sleeves, and other transmission components are given in this paper when applying tailored LPC-processes with 2D-treatment.

REFERENCES


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