Enhancing Control of Distortion Through ‘One-Piece-Flow Heat Treatment’

By applying the technology of Low Pressure Carburizing (LPC) and High Pressure Gas Quenching (HPGQ), the distortion caused by heat treatment can be significantly reduced.

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PROPER DISTORTION CONTROL HAS BECOME EVEN MORE IMPORTANT THAN IN PREVIOUS DAYS. DISTORTED GEAR COMPONENTS CAUSE NOISE IN THE TRANSMISSION AND MAY EVEN CREATE PROBLEMS DURING TRANSMISSION ASSEMBLY. DISTORTION HAS A STRONG COST IMPACT, BECAUSE DISTORTED COMPONENTS OFTEN 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, AND
- LESS TOOLING COST FOR HARD-MACHINING.

WITH AN EXCELLENT CONTROL OF DISTORTION FOR SOME APPLICATIONS, HARD-MACHINING CAN BE COMPLETELY ELIMINATED.

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 [1]. Three different types of stress in the material contribute to distortion: Residual stresses, thermal stresses, and transformation stresses.

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 the component is distorted. Figure 1 gives an overview of the potential factors influencing distortion. Walton [2] published the numerous potential factors that are influencing distortion in more detail.

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, that uses 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 or helium is used as quench gas [3] [4].

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. As a result of this, the distribution of the local heat transfer coefficients on the surface of the component are very inhomogeneous (see Figure 2). These inhomogeneous cooling conditions cause tremendous thermal and transformation stresses, and subsequently distortion, in the component. During HPGQ only convection takes place, which results in much more homogenous cooling conditions [5].

Significant reductions of distortion by substituting oil quench with HPGQ have been published [6]. 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-bar to 20-bar. A frequency converter controls the gas velocity. Typical gas velocities range from 2 m/s to 15 m/s depending on the part geometry and the steel grade of the component. Figure 3 shows a typical industrial system for the HPGQ process. The batches for such systems consist of several layers of production parts, so called “multiple layers.”

ONE-PIECE-FLOW 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 towards a one-piece-flow of production (see Figure 4). The goal is to move single parts from operation to operation instead of moving batches of parts. This one-piece-flow,
OPF, production system would realize a continuous flow of production parts and would avoid huge efforts for storage and transportation of parts between operations [7], [8]. 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 5 shows a new synchronized heat treatment module for one-piece-flow production, which was developed by ALD Vacuum

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Figure 4: Gear manufacturing with central hardening shop and with “one-piece-flow” integrated manufacturing lines.

Technologies (patent pending). 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 (synchronized heat treatment),
- 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 then individually unloaded from it, so the continuous flow of single parts is established.

Figure 5: SyncroTherm heat treat system (single layer treatment; to allow for “one-piece-flow” production, the parts are individually loaded on the tray and the treatment cycle of the tray is synchronized with the machining operations).
In comparison to treatment of big batches in multiple layers, the single treatment provides:

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

All the variations from layer to layer are eliminated, which leads to reduced 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 [9].
DISTORTION STUDY: COMPARISON BETWEEN MULTIPLE AND SINGLE LAYER TREATMENT

A distortion study was initiated to quantify the improvement in distortion control when switching from multiple-layer to single-layer treatment. A reaction internal gear from a 6-speed automatic transmission was chosen as test component. The reaction internal gear has an outer diameter of 152 mm, contains 103 internal teeth, and is made of 5130 material. A picture of the part is given in Figure 6. The tests with multiple-layer treatment were performed in a ModulTherm system (see Figure 3), while the tests with single-layer treatment were performed in a SyncroTherm system (see Figure 5). In both cases, the LPC process was applied at 900°C using acetylene as carburizing source. Helium was used as quench medium for HPGQ in the ModulTherm system and the parts were quenched with an optimized dynamic quenching process as described by the authors earlier [10]. Nitrogen was used in the SyncroTherm system as quench medium for HPGQ.

As of today, the serial production of these internal gears takes place in ModulTherm systems with multiple-layer treatment. To analyze the distortion data from the ModulTherm system, a random load from the current standard production process was used, and complete load sizes were treated [10]. 48 pre-measured parts were equally distributed into different layers of the 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. A picture of the load is shown in Figure 7. In the SyncroTherm system, four tests were performed with single-layer treatment with eight parts placed each time on the tray (see Figure 8). All fixturing was made of carbon-reinforced carbon (CFC) material. 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 populations of parts.

All measurements were performed with a CNC analytical gear-checker. Figure 9 shows the inspection of a gear with the probe of the gear-checker moving along one tooth of the gear. Four teeth were inspected for each gear, and both left flank and right flank were examined per tooth. Figure 10 shows a comparison of the helix angle variation, Vbf, of the right flank measured for the multiple-layer treatment (ModulTherm) and for the single-layer treatment (SyncroTherm). The already low values of Vbf from multiple-layer treatment were further reduced when applying single-layer treatment.

The average and the standard deviation of helix angle variation, Vbf, after heat treatment is given in Figure 11 for both flanks. While the average variation of the left flank was only slightly reduced, the standard deviation was reduced by 30% down to 7 microns when switching from multiple- to single-layer treatment. For the right flank, the average of Vbf was reduced by 30% and the standard deviation of Vbf was reduced by 45%.

Figure 10: Helix angle variation Vbf after heat treatment (right flank); comparison between multiple-layer treatment (one test in ModulTherm) and single-layer treatment (four tests in SyncroTherm).
The lead taper of the reaction internal gears after heat treatment with multiple layers is shown in Figure 12 and the lead taper after treatment with single-layer treatment (four tests) is shown in Figure 13. For the treatment in multiple layers, the two layers from the bottom show a different behavior than the other layers with a change of sign. This means that the “gradient of tooth width” is different for the various layers. For the single-layer treatment, the lead taper has the same direction for all parts. This means that in future optimizations, there is a chance to reduce lead taper when treating this component in a single layer.

When evaluating and comparing heat treat distortions, in most cases the change of geometry from green to the treated component is considered. Figure 14 shows the standard deviation of the change of helix angle FHb through heat treatment. Clearly there is less variation in FHb when switching from multiple- to single-layer treatment. For the left flank, the standard deviation was reduced by 43% and for the right flank it was reduced by 40%, down to 3 microns. The change of Helix variation Vfb through heat treatment is shown in Figure 15. When switching from multiple-layer treatment to single-layer treatment, the average change of the right flank was reduced by 64% and the standard deviation of the change was reduced by 36%.

The lower amount of helix angle variation of the parts from single-layer treatment indicates that they are flatter after heat treatment, as compared to the ones from multiple-layer treatment. In this distortion study, the values from multiple- and single-layer treatment were compared when applying the same carburizing temperature of 900°C. In future works, the results from multiple-layer treatment and carburizing at 900°C will be compared with the single-layer treatment and carburizing at 1050°C.

INTEGRATED MANUFACTURING LINE
As described before, the one-piece-flow heat treatment provides the opportunity to integrate the case-hardening process into a fully automated manufacturing line. Such a line is shown in Figure 16. This line consists of several modular production segments. The “green”
blanks enter the system from the left. The first operation is the green machining unit (turning, hobbing, chamfering, and deburring) followed by the synchronized heat treat unit and then the hard machining unit (hard turning/grinding, gear hard finishing, and washing). Finished gear components leave the system on the right and are ready for assembly.

The level of automation can be chosen from “Chaku-Chaku” to “fully automated” for all units. “Chaku-Chaku” means, in this context, that an operator is manually loading the machines. Tracking of parts and quality documentation of all operations is done on one central computer. The advantages of this synchronized manufacturing line are:

- Line OEE 85% high value stream due to one-piece-flow process chain (OEE = overall equipment efficiency);
- Standardized processes, products, equipment, infrastructure & organization;
- Line cycle time 10 - 20 - 30 sec.; strictly synchronized; scalable according to the pacemaker process;
- Throughput time < 4 hours incl. heat treatment (HT-LPC & HPGQ);
- Compact installation; required space is only 50% of the space required for conventional production.

The potential layout of two integrated manufacturing lines can be found in Figure 17.
SUMMARY AND FUTURE WORK

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, reduces the amount of distortion as compared to conventional case hardening technologies. The amount of distortion can be further reduced when switching from multiple-layer LPC treatment to single-layer LPC treatment (one-piece-flow).

This was demonstrated in a comparative study on a Reaction Internal gear from a 6-speed automatic transmission. The standard deviation of helix angle variation Vbf after heat treatment was reduced by 30% for the left flank and by 45% for the right flank, after switching from multiple-layer to single-layer LPC treatment. When looking at the change of helix angle FHb through heat treatment, the standard deviation was reduced for the left flank by 43% and for the right flank by 40%.

Furthermore the single-layer treatment offers the possibility to manufacture gear components following the “one-piece-flow” philosophy. It is therefore possible to fully integrate heat treatment into the manufacturing line and to synchronize heat treatment with gear machining. This total integration of heat treatment into the manufacturing line allows for significant savings in logistical efforts, efforts for documentation, and quality assurance. On top of this, with the fully-integrated line, the turn around time of a typical gear wheel can be drastically reduced from a few days down to less than four hours.

REFERENCES


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