

Vacuum heat treatment and high pressure gas quenching – Aspects in Distortion Control

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This technical article reviews high pressure gas quenching technique using different quenching processes for improvement of part quality, cost and mechanical properties.

Gas quenching represents an environmental friendly alternative to commonly used atmospheric oil quenching. ECM has developed innovative quenching processes for quality and performance improvement on finished parts in the automotive and gear industry. The goal is to reduce the level of distortion as well as the increase of mechanical properties. Industrial applications will be shown with detailed data. Explanations will be given on improvements and manufacturing process cost savings. These processes could be directly applied to existing processes for global cost reduction and quality improvement or for future products which need increased performance and higher levels of quality.

Low Pressure Vacuum Gas Carburizing (LPC) with High Pressure Gas Quenching (HPGQ) has received much attention recently. Batch and batch to batch heat treatment variability for case depth, core hardness and part distortion is a significant concern to the end user. A variable speed quenching process has

been developed with results that show significant improvement in distortion. Process development including extensive cooling curve analysis and component testing will be discussed.

This paper introduces process developments in low pressure carburizing by

using either High Pressure Gas Quenching with ECM StopGQ® or ECM StepGQ® interrupted gas quenching. Comparisons of distortion measurements and mechanical properties that were measured from the processes are discussed. This will show how the optimization of gas quenching can improve both distortion and fatigue strength through development of various heat treatment cycles.

Gas quenching process StepGQ®

To minimize quench-induced deformation, it is recommended that the gas quenching be performed in steps, thereby taking advantage of the flexibility of the process. Substantial gains in terms of quality can be achieved by ensuring that the quenching process follows the continuous cooling diagram of the steel as closely as possible. This has been confirmed by tests on components subject to a high degree of deformation.

In gas quenching, the intensity of the process can be controlled by varying two parameters: the gas pressure and mixing rate (**Fig. 1**). This flexibility provides some interesting options for components subject to distortion. Step quenching with variations in intensity can also be used to minimize distortion and has been confirmed with collaborative testing through outside partners.

For maximum consistency, the furnace load temperature is first lowered at the end of the heat treatment and, as a first step, the quenching is initially low in severity with moderate gas pressure and mixing. Quenching intensity increases to avoid the formation of bainite and pearlite phases as much as possible (**Fig. 2**).

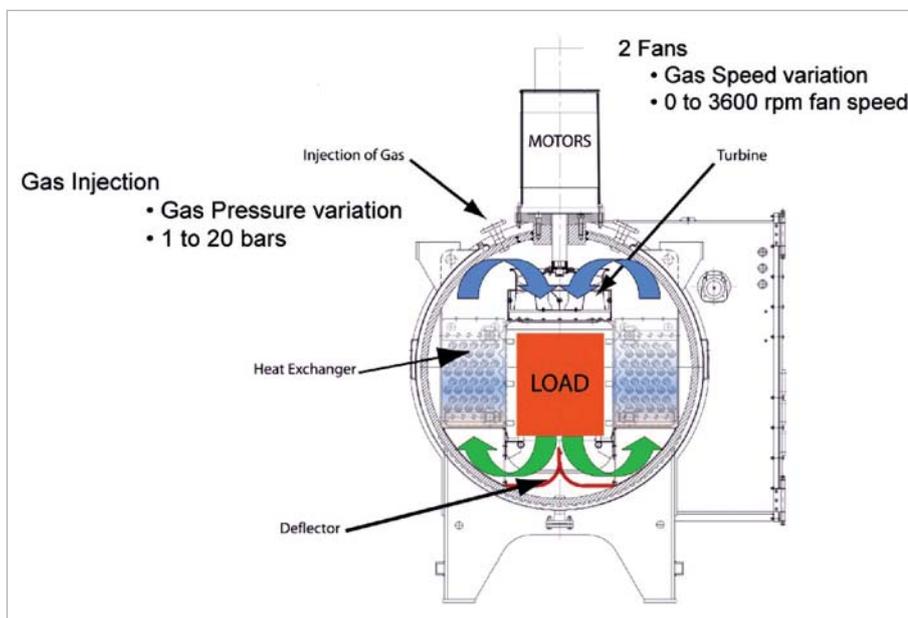


Fig. 1: Cell Design Overview

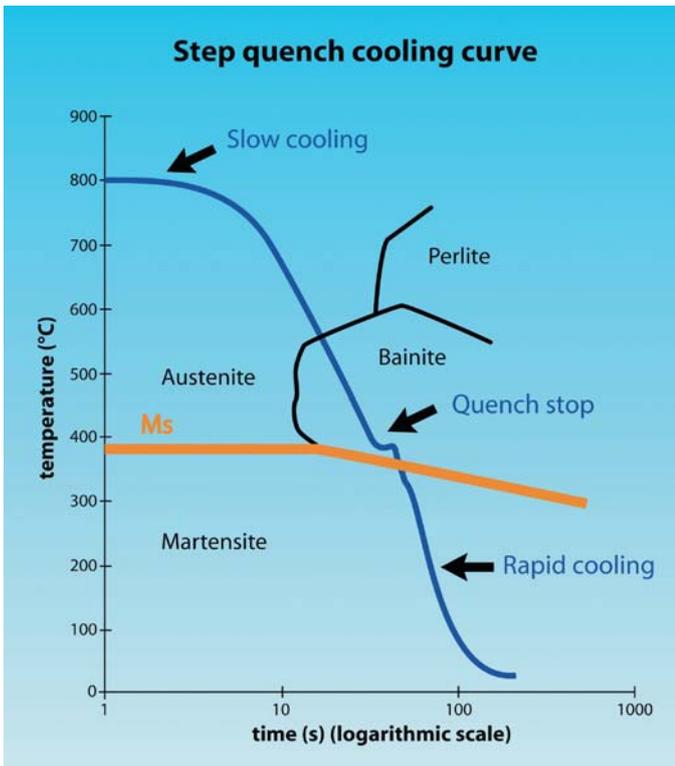


Fig. 2: CCT diagram

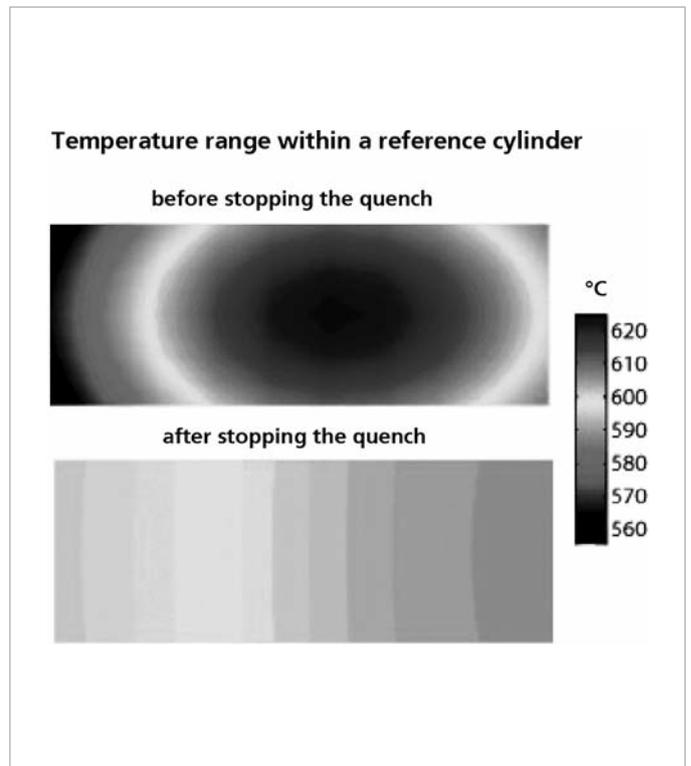


Fig. 3: Quenching Modeling

For the second and more critical step, the quenching is paused for a few seconds before the martensite transformation stage. Gas mixing is suspended, thereby promoting conduction within the component. This prevents an excessive temperature difference between the surface and core of the component (Fig. 3), a factor inducing residual stress and thus deformation during the martensite transformation.

The last step in the process is designed for maximum quenching. The faster cooling rate and subsequent transformation to martensite resulted in improved mechanical properties of the steel.

Step quenching enables the process intensity to be adjusted at critical stages



Fig. 4: Ring gears

where deformation is more likely to be produced. Viewed as a whole, the formula can be likened to a three-stage cooling process where the continuous cooling transformation (CCT) diagrams of the steel are closely followed.

Testing was conducted on ring gear components using a 5130 steel (Fig. 4).

The results of step quenching have been compared with o-called "direct" quenching at constant intensity.

The distortion measured on the flank of the tooth was reduced on average from 13 to 4 μm which was below the crowning deformation threshold. On transmission ring gears, out-of-round wear phe-

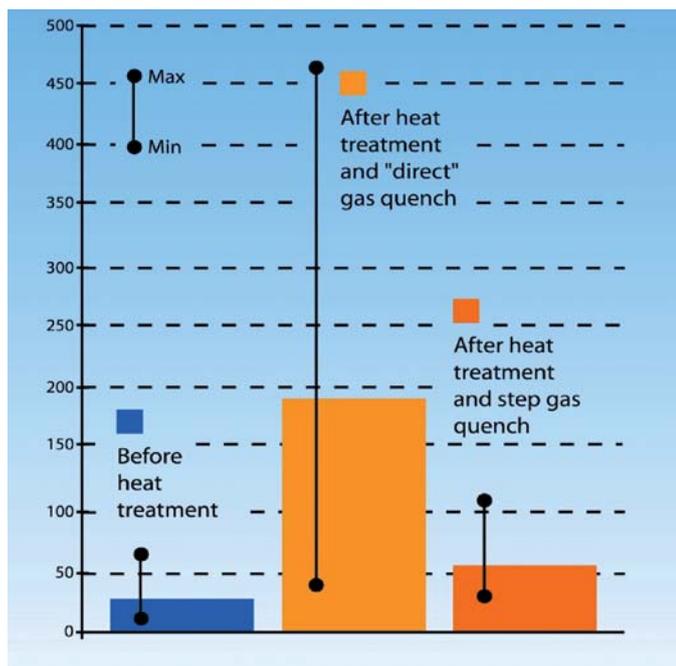


Fig. 5: Ring Gear

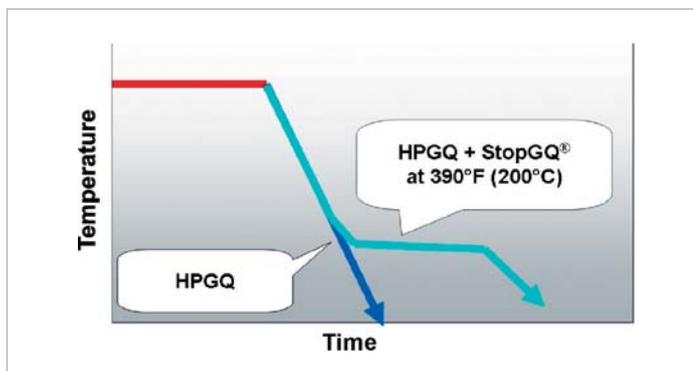


Fig. 6: StopGQ Quenching

nomena (Fig. 5) are reduced by a factor of four. Moreover, in both the above cases, the results obtained are highly consistent throughout the furnace load. Therefore, the level of distortion and consistency during the heat treatment process can be managed.

In the field of deformation control, the alloy composition plays a determining role. For steels that have been developed for gas quenching, a fairly low gas pressure can be applied that is between 5 and 12 bars. This reduces thermal shock and thus minimizes distortion. In addition, the CCT diagram for steels of this type may exhibit bainite and pearlite "noses" shifted to the right. As a result, the cooling diagram indicates that only the austenite and martensite phases result, thereby approaching the theoretical ideal case. To optimize the reduction in deformation, both the quench cycle and the material need to be adapted.

By anticipating and minimizing deformation, step quenching optimizes the entire heat treatment process and thus reduces the total production cost through fewer rejects, less straightening operations and fewer defect repairs. The

step quenching process is a quality assurance measure for many parts. It is not necessarily applicable for all parts and may be dependent on the shape of the component. Those parts that are not subject to deformation do not need it. For other components, step quenching opens up new prospects. ECM has a specific method and specialized tools, such as the Quench software developed in collaboration to establish the ideal formula.

Quenching process StopGQ®

Increased performance requirements in automotive and other industries demand higher strength characteristics from components such as gears and pinions. Those requirements translate

into a need for improved impact properties and fatigue strength. The technical solution to address the need for expanding the performance envelope has required the development and optimization of new processes. A research program was launched to see the flexibility of low-pressure vacuum carburizing in combination with high-pressure gas quenching (LPC + HPGQ) to investigate several vacuum processes:

- LPC + HPGQ
- LPC + HPGQ + Tempering
- LPC + StopGQ

Marked improvements in mechanical properties were found as a result of the optimization of quench parameters. The conventional process, LPC + HPGQ + Tempering, was used as a benchmark for all tests.

Once a workload has been hardened or case hardened, tempering is necessary. Conventional high-pressure gas quenching is intended to bring the entire workload to room temperature as rapidly as possible. Interrupted quenching involves halting the cooling process in the temperature range of 350–400°F (180–200°C) and introducing an isothermal hold (Fig. 6) in order to perform an "auto-tempering" step in the gas quenching cell. The instrumentation of

Table 1: Specification targets for test gears

Steel Grade	Effective Case Depth 52.5 HRC (550 HV) inches (mm)	Surface Hardness (HV 20)	Core Hardness (HV 50)
5130	0.020-0.030 (0.5-0.7)	690-900	320-500

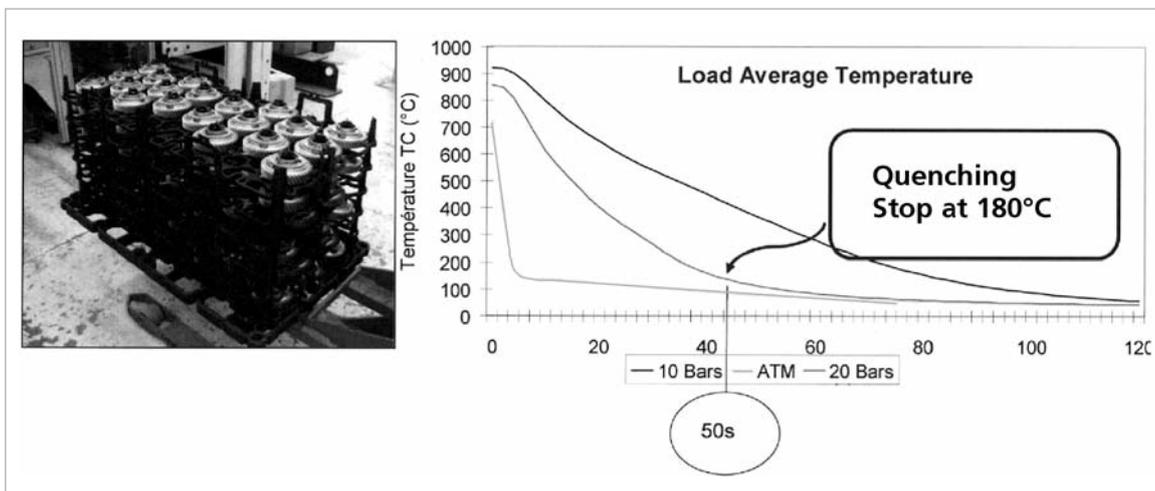


Fig. 7: StopGQ quench time versus pressure relationship



Fig. 8: 5130 Gear Test Load

full-load trials of gears (Fig. 7) helps to determine the correct time delay before initiation of quench interruption as a function of quench pressure.

Specification targets (Table 1) were selected for gears (Fig. 8) of SAE 5130 (29MnCr5) material.

Hardness and effective case depth results achieved targeted values (Table 2). This confirmed that there was no metallurgical difference as a result of

this heat treatment process to influence fatigue strength results.

One additional mechanical property test employed to assess the heat treatment process was to determine impact properties. Impact samples were tested in a pendulum type impact tester at 50J (Fig. 9).

The result of impact testing when compared to LPC+HPGQ revealed a strong benefit of tempering on impact proper-

ties. Also noteworthy was the improvement over LPC+HPGQ that was achieved by interrupted quenching. These results indicate that additional testing is required to optimize results. Another mechanical test that was employed was that of rotating bending fatigue using a notched sample geometry (Fig. 10). The test was run for 1×10^7 cycles.

The results of rotating bending fatigue testing indicate that Stop GQ process improves strength values over those of LPC+HPGQ or LPC+HPGQ+Tempering (Fig. 11).

An improvement in fatigue strength was realized using the "auto-tempering" effect achieved by the StopGQ quenching. A summary of mechanical properties is presented in Fig. 12.

Dilatometry studies showed less contraction with an interrupted quench compared to direct high-pressure gas quenching (Fig. 13). During the StopGQ quench, quadratic martensite is transformed into cubic martensite plus ϵ carbides, resulting in an automatic tempering effect. This was demonstrated by rupture analysis which revealed higher ductility in the core of the material processed (Fig. 14).

These trials allowed the following conclusions to be reached:

1. The metallurgical parameters which act on resistance in fatigue inflection of gear teeth for a fixed hardened depth were better understood.

Table 2: Hardness and Case Depth Summary

	Thermal Treatment	Hardness (HV)		Case Depth Inches (mm)
		Surface	Core	
5130	LPC + HPGQ	885	440	0.015 (0.39)
5130	LPC + HPGQ + Tempering	800	445	0.015 (0.40)
5130	LPC+HPGQ with StopGQ Quenching	872	460	0.018 (0.45)

Note: Quench pressure was 13 bar (nitrogen) for each test run.

Table 3: Steel Grade Case Depths

Steel Grade	Case Depth E 550	Core Hardness Hv 50	Surface Hardness Hv 20
5115 SAE	0.7mm (.029")-0.9mm (.035")	300-400	680-900

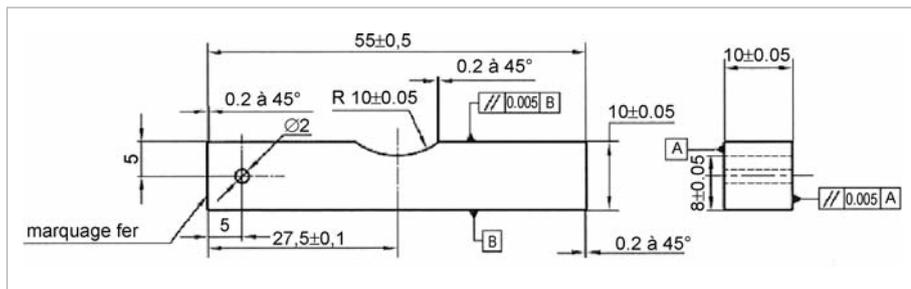


Fig. 9: Impact sample

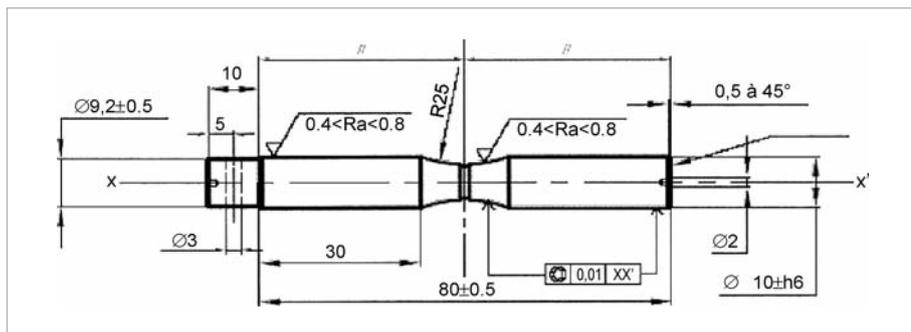


Fig. 10: Rotating bending fatigue sample

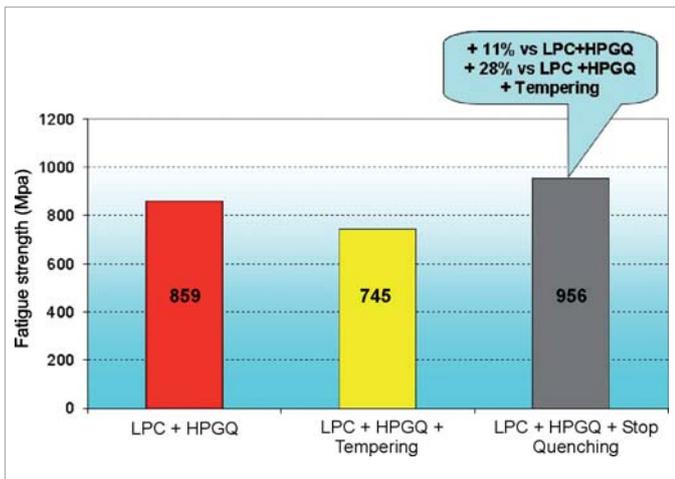


Fig. 11: Improvement of Rotating Bending Fatigue

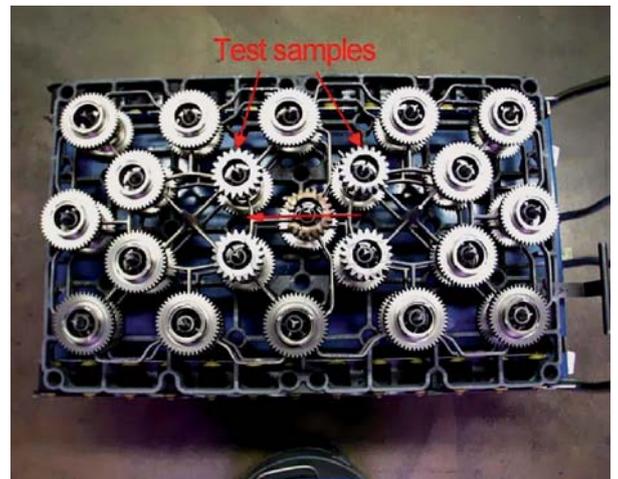


Fig. 15: Planetary gears

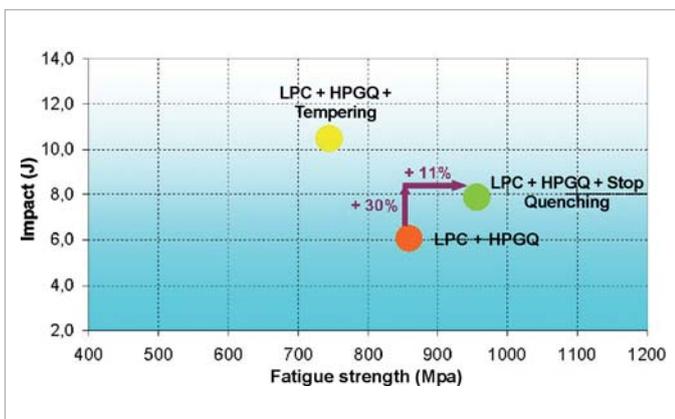


Fig. 12: Summary of StopGQ®. Benefits versus LPC+HPGQ

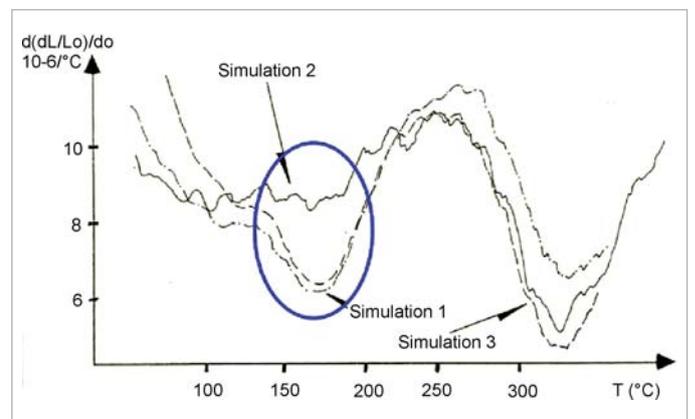


Fig. 13: Dilatometry Studies of the StopGQ® Quenching Method

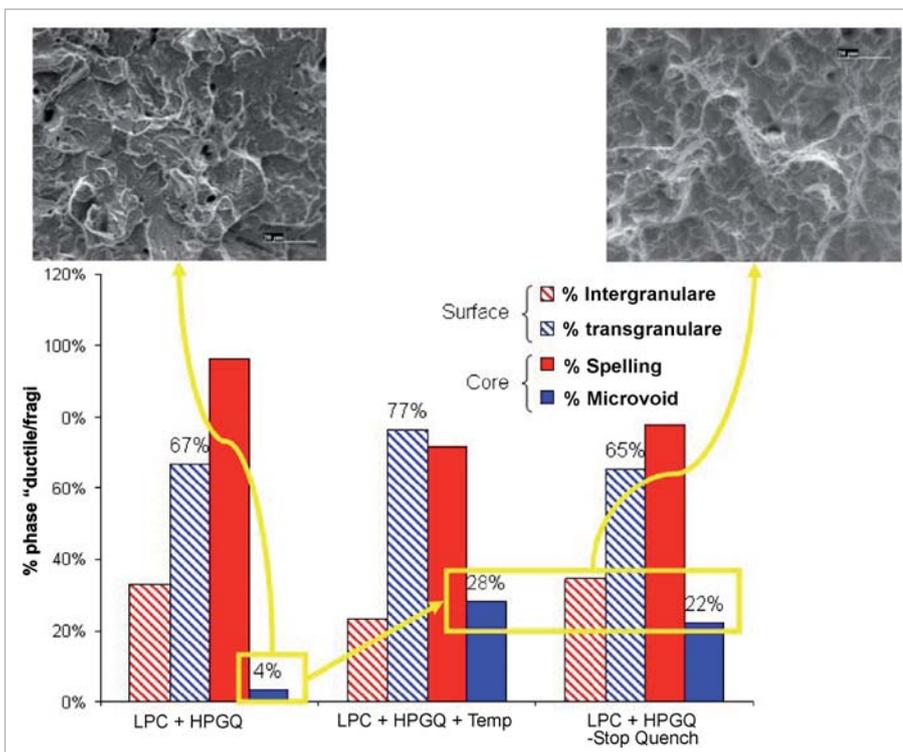


Fig. 14: Rupture Analysis Comparison by Process

2. Results indicate improvements in fatigue resistance of gear teeth compared to low-pressure vacuum carburizing treatments.

Case Study

Tests at found better fatigue strength with interrupted gas quenching. Tests on two sets of transmission gears have confirmed gains in fatigue strength linked to a stop during gas quenching. These results are very encouraging when considering that tomorrow's gearboxes will have to be more powerful without an increase in size or weight.

The flexibility of gas quenching offers potential for improvement in mechanical properties. This is the conclusion of several series of tests conducted on transmission gears. By testing a gas quenching procedure known as "StopGQ" (Stop Gas Quenching) characterized by a long stoppage during quenching in the martensite phase, a

Table 4: Hardness and effective case depth

Steel Grade	Process	Hardness		Case Depth (mm)
		Surface (HRC)	Core (Hv30)	
5115 SAE	LPC+HPG Q	62.2	370	0.85/0.8
	LPC+ StopGQ	60.5	370	0.85/0.75

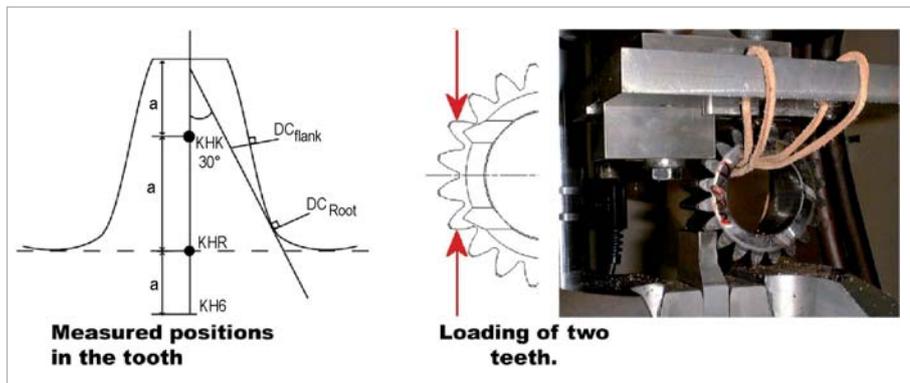


Fig. 16: Fatigue Strength Testing Evaluation

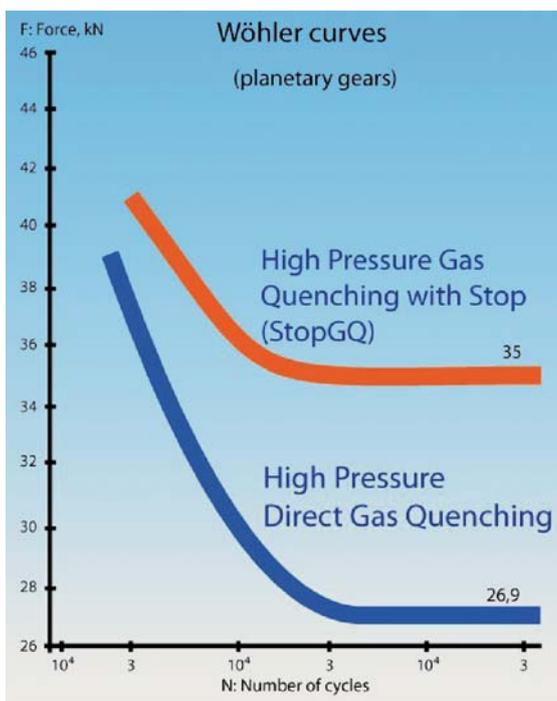


Fig. 17: Wöhler curves

30% improvement was obtained in fatigue strength compared to direct, continuous gas quenching. This could have a major impact on processes and products.

Specification targets (Table 3) were selected for planetary gears made from a 16MnCr5 steel grade. In the trials the test samples were loaded on a tray together with gears of a similar size (Fig. 15).

Hardness and effective case depth achieved targeted value (Table 4).

The gears were fatigue tested in a hydraulic MTS810 resonance test rig

(Fig. 16). Two teeth were loaded with a sinusoidal force that used a frequency of 18 Hz. The R-value (F_{max}/F_{min}) was kept constant at 0.1.

The values shown by the Wöhler curves were the fatigue strength limit of the gear after two million cycles were found to be $\sigma_a = 685$ MPa (with $R = 0.1$) for the "StopGQ" gas quenching method compared to $\sigma_a = 525$ MPa for direct gas quenching (Fig. 17).

An examination of cracked zones resulting from the fatigue tests revealed transgranular fractures with LPC+ STOPGQ– these fractures are typically intergranular in components cooled by high pressure gas quenching (Fig. 18). The differences in fracture behavior and in the fatigue strength results are due to the StopGQ Process. During StopGQ, parts are held at 200°C, then martensite is tempered with a microstructure modification.

Conclusion

With improved fatigue strength, the torque of existing transmissions gears could be increased through low pressure gas quench carburizing.

One other possibility is the design of thinner, lighter gears or gears made from a less expensive steel grade with modifications to the alloy content.

Stop gas quenching could contribute to the production of less expensive, more fuel-efficient vehicles by providing opportunities for alternate component design and improvement in power density.

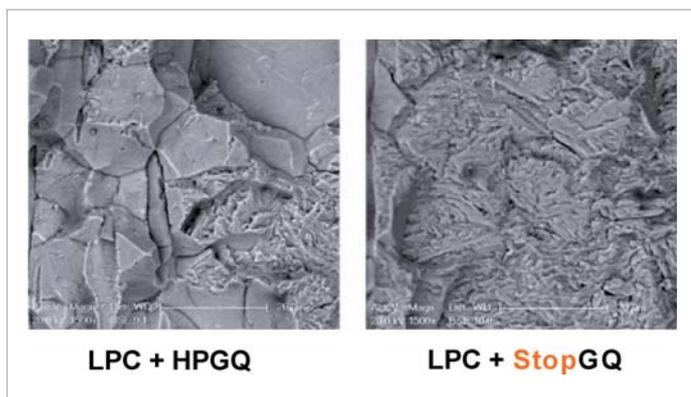


Fig. 18: Fracture surface

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