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Improving Gear Performance by Intensive Quench

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Abstract

To meet a goal of at least a 25% improvement in helicopter gear tooth bending fatigue life, a project was initiated by DCT under US Army Aviation Technology Directorate sponsorship to improve the compressive residual surface stress state by applying intensive quenching in place of conventional oil quenching. The feasibility was demonstrated and reported upon using a carburized and quench hardened notched bar sample subjected to three point bend testing. This paper reports the results of single tooth bending fatigue tests for carburized and quench hardened Pyrowear® 53 steel gears. The fatigue test data show that intensively quenched gears had higher life in comparison to conventionally heat treated gears. The surface residual stress state had a higher magnitude of compression for the intensively quenched gear than for the oil quenched gear. Computer simulations of the heat treat processes provided a sound understanding of why these quenching methods produced different bending fatigue strength for essentially the same martensitic microstructures and hardness levels.

Introduction

Helicopters are often referred to as flying fatigue macjines. In particular, the life of transmission components is critical. The US Army Aviation Technology Directorate (AATD) has a goal of improving the power density of the transmission without degrading fatigue life. While this could be accomplished by redesigning the gearbox, a more attractive option in terms of time and cost is to enhance the fatigue strength of the existing components by increasing the magnitude and depth of residual compression in the parts. The substitution of intensive quenching in place of conventional oil quenching has demonstrated the feasibility of this approach. Previous work using three point bending fatigue tests for carburized Pyrowear 53 steel bars has shown that intensive quenching can increase fatigue life by more than the aim of 25%. This paper extends that work to examine quench hardening of a spur gear and resultant single tooth bending fatigue strength.

Pyrowear is a registered trademark of Carpenter Technology Corp.

Steel

Pyrowear 53 is the gear steel of choice for military helicopter transmissions because of its resistance to softening at elevated temperatures. This ability has proven beneficial as field experiences have shown that the transmissions can lose lubricant and still provide a minimum of 30 minutes of flying time.

Table 1: Pyrowear 53 Steel Chemistry

Weight Percentage of Alloying Element	
Carbon	0.1
Manganese	0.35
Silicon	1.0
Chromium	1.0
Nickel	2.0
Molybdenum	3.25
Vanadium	0.10
Copper	2.0

The gear manufactured for these single tooth bending tests is shown in Figure 1. It is a 40 tooth straight spur gear with a module of 2.54 and a face width of 0.25 inches (6.35 mm).

Heat treatment

The baseline heat treatment process for Pyrowear 53 gears is given in Table II. For aerospace gears, including this gear, only the functional surfaces are carburized, and all other surfaces are copper plated to prohibit carbon penetration. A total of 34 gears were vacuum carburized in one batch, and then half the gears were quench hardened following the baseline process, and the other gears were heat treated following the IQ process route.

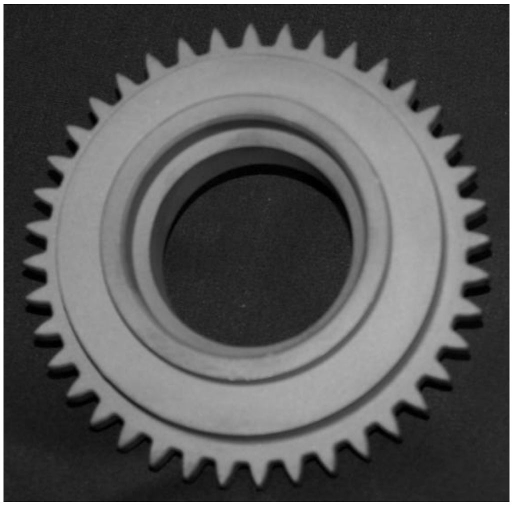


Figure 1. Carburized and quench hardened spur gear.

Table 2: Heat Treat Schedules for the Two Sets of Gears.

	Baseline OQ Process	IQ Process
Vacuum Carburize	8 hours at 1700 F	8 hours at 1700 F
Subcritical Anneal	2 hours at 1175 F	2 hours at 1175 F
Austenitize & Quench	1675 F, quench in oil at 150 F	1675 F, intensive quench to 70 F
Deep Freeze	1 hour at -100 F	1 hour at -100 F
Double Temper	2 hours at 450 F	2 hours at 450 F

Heat Treat Process Simulations

While gears were being manufactured, heat treat process simulations were conducted to examine the levels of residual stress and dimensional changes that could be expected from both processes. These simulations proved to be extremely useful, as explained below.

The predicted carbon profiles at the center of the root, the fillet or corner of the root, and at the pitch diameter are shown in Figure 2. These predicted data sets were extracted from a 3D model of the gear.

The test gear dimensions and exact process conditions are proprietary to one of the helicopter OEM's. Deformation Control Technologies (DCT) was not provided the green gear dimensions, and no estimates of residual stress, hardness, or carbon profile were available. While the amount of finish grind stock, 0.005 inches (0.13 mm), was provided to DCT, as were the final gear dimensions, DCT had to determine the amount of growth that accompanied each process route, so that the residual stress state after hardening and before finish grinding could be compared. It

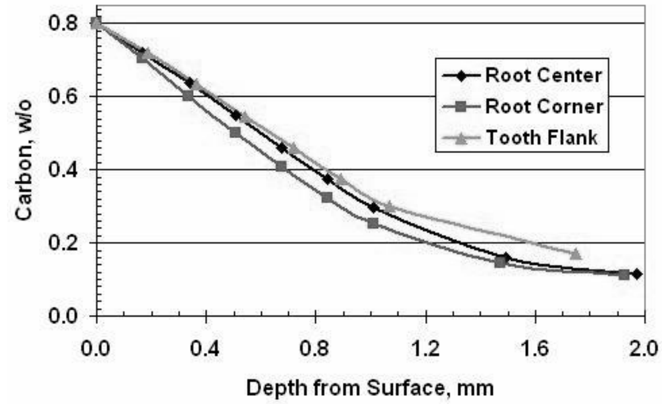


Figure 2. Carbon profiles at the indicated locations.

was also necessary to compare growth differences between the baseline and IQ processes in order to assess how the metal removal would affect the differences in residual stress. In other words, could differences in growth due to heat treatment plus the differences in stock removal to achieve identical final gear dimensions remove any differences in the residual stress state that might exist after quench hardening? This was critical information to the study, and simulation provided the method to answer this question.

Using the DANTE heat treat simulation software package, DCT determined that a baseline gear would grow approximately 0.0013 inches (0.033 mm) per side and the IQ processed gears would grow approximately 0.003 inches (0.076 mm) per side, or 0.0017 inches (0.043 mm) more than the baseline gears, see Figure 3. This meant that the standard 0.005 inches would be ground from the baseline gears and that 0.007 inches (0.18 mm) of stock would be ground from the intensively quenched gears.

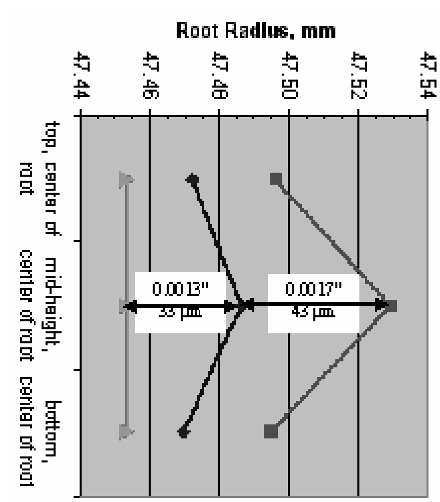


Figure 3. Radial location of the gear root, showing the initial or green location(▸), and the heat treated locations for the baseline (◆) and IQ (■) processes.

The same simulations predicted the residual stress states that would be produced by the two quench hardening processes. These are shown in Figure 4, as are the depths of stock to be removed. From Figure 4, it is clear that the simulations predict that the IQ route would produce a significant increase in residual compression over the baseline process. Furthermore, the compressive field in the IQ processed gear was predicted to extend deeper into the gear body than that of the baseline gear. With this information, DCT determined that even with the difference in stock removal that a significant difference in residual compression would exist after stock removal.

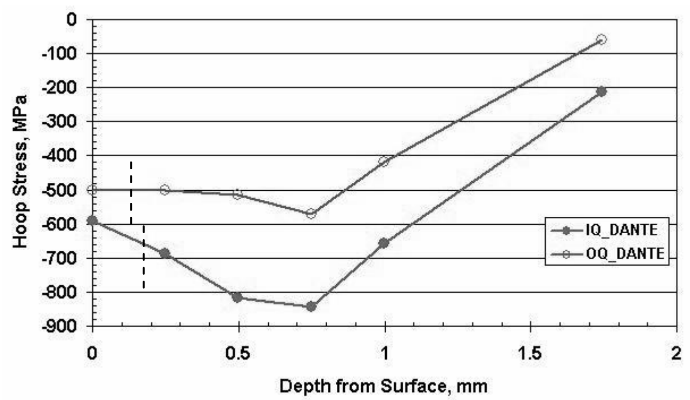


Figure 4. Predicted residual hoop stress at center of tooth root for the baseline and IQ processes. The grinding stock removal is indicated by the dashed lines.

Gear Characteristics

After heat treatment and final grinding, one gear from each batch was characterized in terms of microstructure, microhardness of the case and core, and residual stress state. The microstructures for both quenching methods were tempered martensite in the case and core pf the gear tooth. The measured microhardness of the intensively quenched gears was slightly higher than that of the oil quenched gears in the carburized case, i.e HRc 58 to 60 for IQ gears vs. HRc 58 to 59 for OQ gears, and these values were measured after grinding. These values are lower than expected for this carburizing schedule since they were measured after surface grinding; values ≥ HRc 60 were measured on witness bars. The core hardnesses were the same for both gear sets, i.e. HRc 42.

X-RAY diffraction was performed on a baseline (OQ) gear and an intensively quenched (IQ) gear to compare residual stress values. Similar to the simulations, hoop stresses calculated from the X-RAY diffraction (XRD) measurements showed that the intensive quenching process produced deeper compressive surface stress in the tooth root, see Figure 5. The agreement between the predicted hoop stress and measured hoop stress is very good for the IQ gear, while the predicted hoop stress profile for the OQ gear is slightly more compressive than that from XRD measurements. The XRD data demonstrates the difficulty of stress depth profiling at complicated geometric locations such as a gear root and the issue of accuracy for this method.

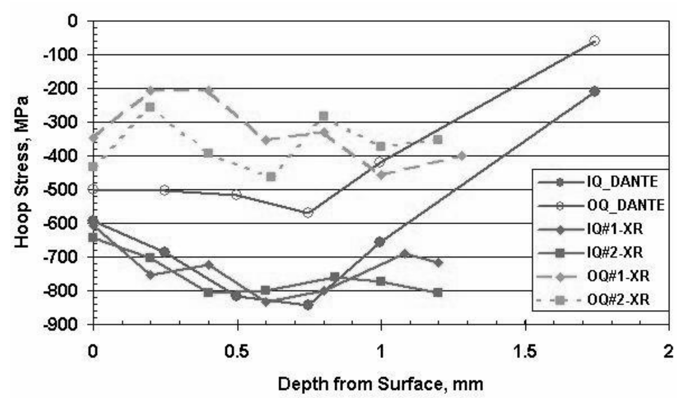


Figure 5. Hoop stress profiles at the center of the root for OQ and IQ gears as predicted by computer simulation and calculated from XRD measurements.

From the computer simulations, the minimum principal stress profile for the root fillet was predicted to be more compressive than at the center of the root for both sets of gears. For the OQ gear, the minimum principal stress at the surface of the root fillet location was predicted to be 600 MPa, while the predicted minimum principal stress for the IQ gear was -820 MPa. The maximum principal stress at this location was predicted to be -30 MPa for the OQ gear and -60 MPa for the IQ gear.

Single Tooth Bending Fatigue Testing

The gears were tested at Gear Research Institute using a servohydraulic testing machine with a specially designed fixture to apply a bending load to two teeth. A schematic of the fixture is shown in Figure 6. One tooth was loaded by a tup connected to the ram of the machine which cycled at 40 Hz, while a second tooth was seated against a shaped anvil. The upper and lower anvils were shaped such that no teeth needed to be removed for load application. The ratio of minimum to maximum load was fixed at 1:10 so that one root fillet of each contacted tooth was always loaded in tension. The machine shut-off automatically when excessive ram displacement due to tooth cracking occurred. Runout was defined as 10^7 cycles without failure of either tooth. The location of the applied load was determined to be the point of first contact with a mating gear which corresponds to the condition that generates the maximum stress in the gear root fillet. This is the typical failure location due to bending fatigue.

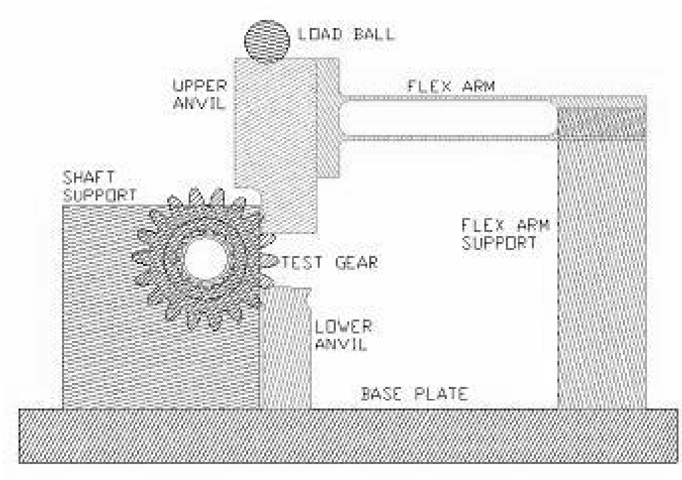


Figure 6. Schematic of tooth bending fatigue fixture at Gear Research Institute.

The fatigue test data for the OQ and IQ gears are shown in Figure 7. Qualitatively, the IQ gears have higher fatigue strength than the baseline OQ gears. The number of runout tests (10^7 cycles) at a given load are indicated along the right side of the figure. Since each test loads two teeth, each runout case produced two data points. A failure produced only one data point, that for the cracked tooth root. Statistical analysis of the fatigue data is in-progress, but initial indications are that that the IQ gears have approximately a 10 % improvement in life over the baseline OQ gears.

Several failures occurred away from the root, and these are indicated as boxed data points in Figure 7. The reasons for these abnormal failures have not been fully determined, although two observations have been made. First, scanning electron microscopy (SEM) of two failure surfaces has revealed sub-surface inclusions of sizes that should not typically be present in VIM-VAR steel such Pyrowear 53. Secondly and of more significance, the edge preparation of the gears, although within specification of the gear, varied from root to root and from gear to gear for both OQ and IQ gears. The scatter in the fatigue data is most likely due to the edge condition. Additional tests are in-progress for gears of each type to investigate this further.

Discussion

The intensive quenching process produced higher compression than the baseline oil quenching processes for these gears, and the corresponding bending fatigue strength was also improved. These findings are in agreement with the results previously reported for three point bend tests for this steel that were carburized and hardened using the same schedules given in Table 2.[1] A higher magnitude of residual surface compression produced higher fatigue strength for parts having similar microstructures and hardness levels.

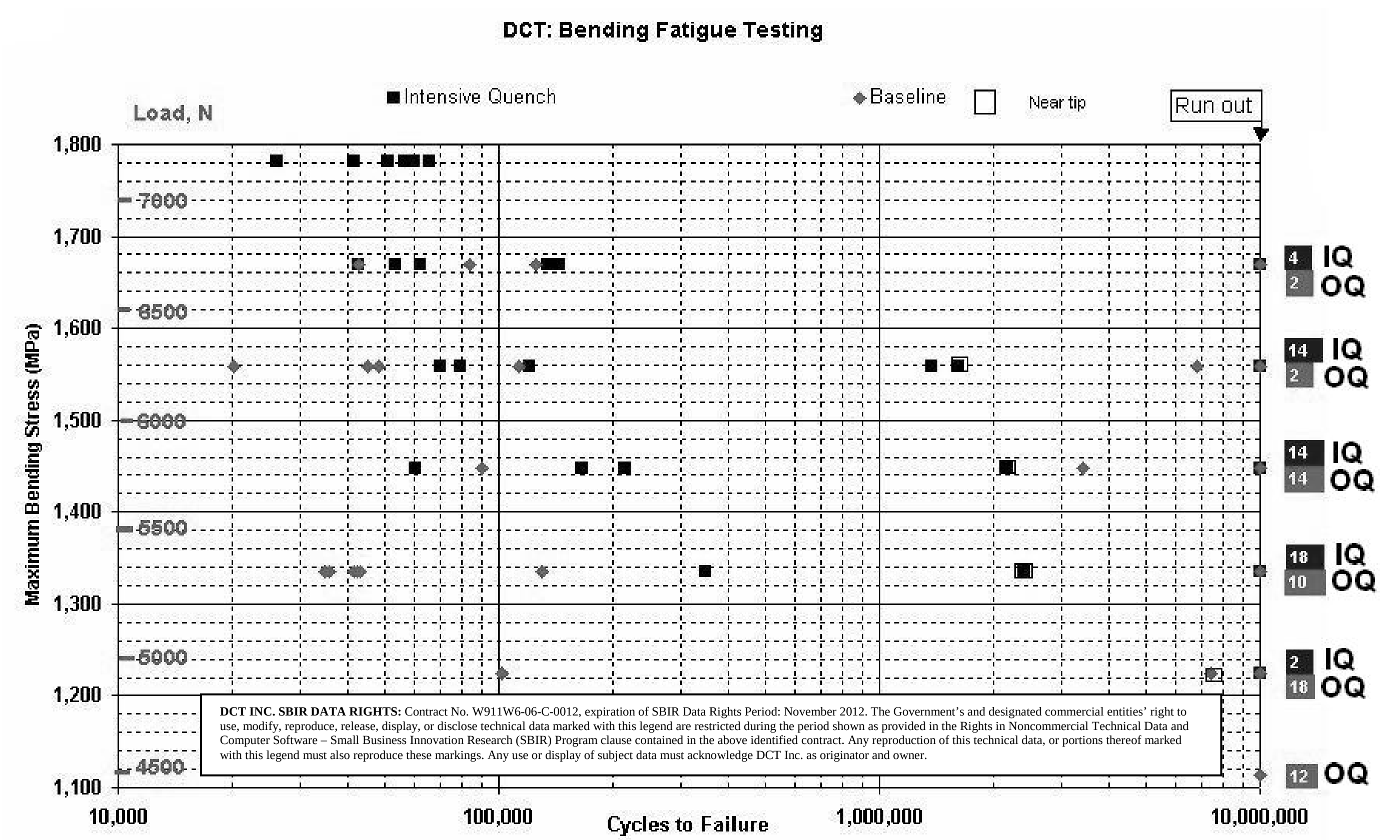
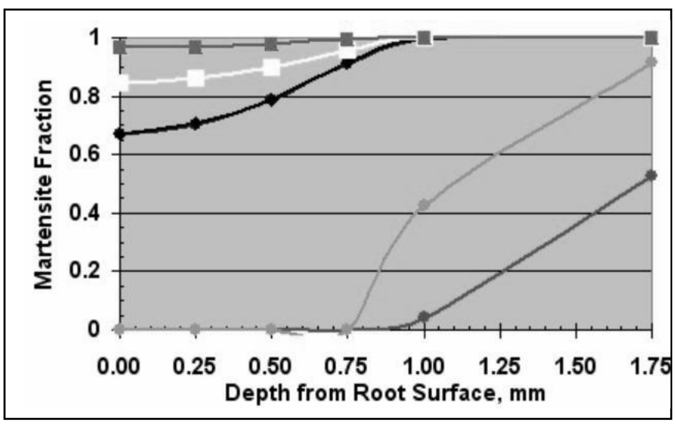


Figure 7. Single tooth bending fatigue data.

Martensite Formation & Evolution of Stress Durng OQ

The underlying reason for the residual stress and the resultant fatigue strength differences between the two heat treatment processes is the difference in the evolution of metallurgical phases caused by the differences in temperature histories during quenching. The heat treat simulations showed a significant difference in the timing of austenite transformation to martensite at specific locations in the gears.

During conventional oil quenching, martensite formation started at roughly the case-core interface and transformation of the high carbon case to martensite occurred after significant martensite had already developed internally, as shown in Figure 8. In fact, with the baseline OQ process, much of the austenite in the case transformed to martensite during the air cooling period after oil quenching. This is in agreement with heat treating experience. Due to a sub-ambient martensite finish temperature in the high carbon surface, the level of retained austenite was high after oil quenching (70% martensite) and after air cooling (82% martensite). After deep freezing, the fraction of martensite in the case rose above 96%, as shown in Figure 8. The final martensite content was this value as tempering converted the final amount of retained austenite to lower bainite.



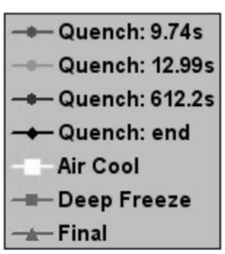


Figure 8. Martensite formation at indicated process steps and step times for the baseline OQ route. These predictions are as a function of depth from the center of the root.

The corresponding evolution of residual stress, as depicted by the maximum and minimum principal stress states change with temperature and the local martensite volume fraction, compare Figures 9 and 10 with Figure 8. As oil quenching starts, the surface austenite cools and is constrained from thermally shrinking by the hotter interior metal, so surface tension develops. As martensite forms below the case-core interface, the internal swelling due to martensite formation pushes the surface into tension; this is most evident in Figure 9 at the 12.99 second quench time. After 612 seconds, the martensite formation for the oil quench step has been completed and the surface tension has been reduced by case martensite formation. At this point, the gear temperature is 60 C and the case still contains a considerable amount of austenite. Cooling to room temperature leads to further martensite formation in the case and deepening compression, see the "Air Cool" lines in Figures 9 and 10. The deep freeze treatment significantly increases surface compression by transforming near-surface austenite to martensite , cf. "Deep Freeze" in Figures 9 and 10. The temperature rise to room temperature does not change the martensite content, but it does slightly decrease compression, cf. "Final" in Figures 9 and 10). Low temperature tempering does not cause an appreciable change in residual stress and the final surface compression is predicted to be about -400 MPa.

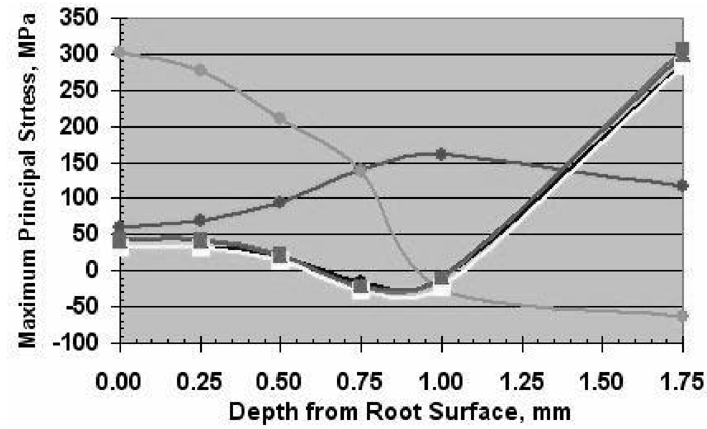


Figure 9. Evolution of maximum principal stress during the baseline OQ process. The legend is given in Figure 8.

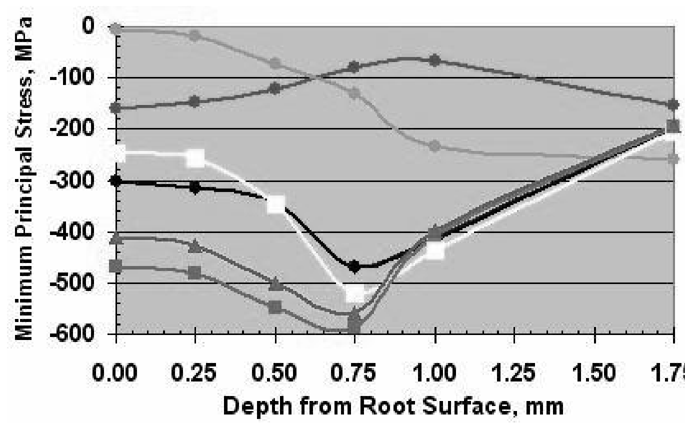
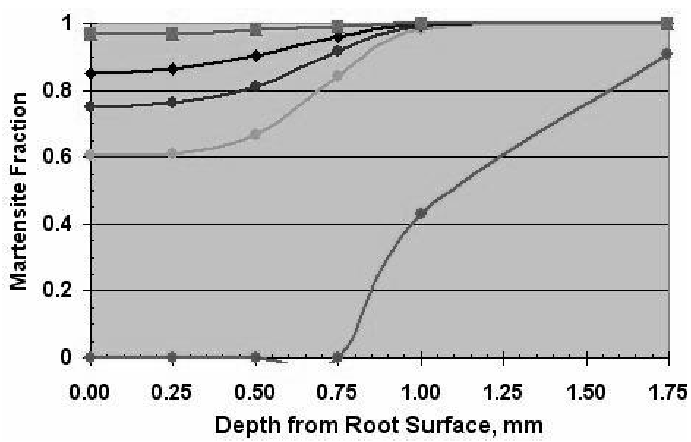


Figure 10. Evolution of minimum principal stress during baseline OQ process. The legend is given in Figure 8.

Martensite Formation & Evolution of Stress Durng IQ

At the end of intensive quenching, the martensite content was predicted to be similar to that of oil quenching and air cooling. However, the timing differences in martensite formation resulted in a significant difference in the development of internal stress during quenching. For intensive quenching, the severe cooling rate initiated austenite decomposition nearly simultaneously in the high carbon case and at the case-core interface of the gear. Figure 11 shows that after 1.5 seconds of intensive quenching, a significant amount of matertensite has formed below the case-core interface. Figure 12 shows that the surface austenite at 1.5 seconds is under considerable tension due to the constraint of the hot core and the subsurface expansion as martensite forms. However, martensite quickly forms in the case to relieve this tension, as the curves for 3.25 seconds and 5.25 seconds of quenching show reduced levels of tension and building levels of compression with the increased martensite fraction in the case. At the end of the IQ step, the martensite fraction in the case is about 85% and the surface is under compressive stress at about -600 MPa. This significant difference in residual stress was maintained during the deep freeze and tempering steps so that the final residual stress state of the intensively quenched gear was more compressive than that of the baseline processed gear, cf. "Final" curves in Figures 10 and 13 for minimum principal stress.



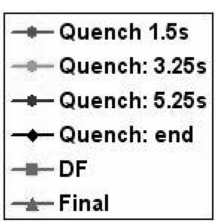


Figure 11. Martensite formation at indicated process steps and step times for the IQ process route. These predictions are as a function of depth from the center of the root.

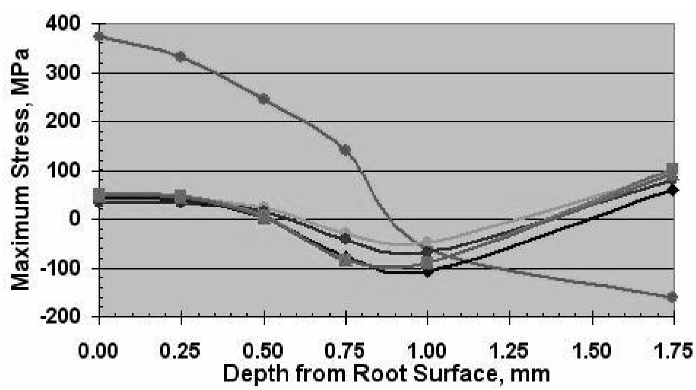


Figure 12. Evolution of maximum principal stress during the IQ process. The legend is given in Figure 11.

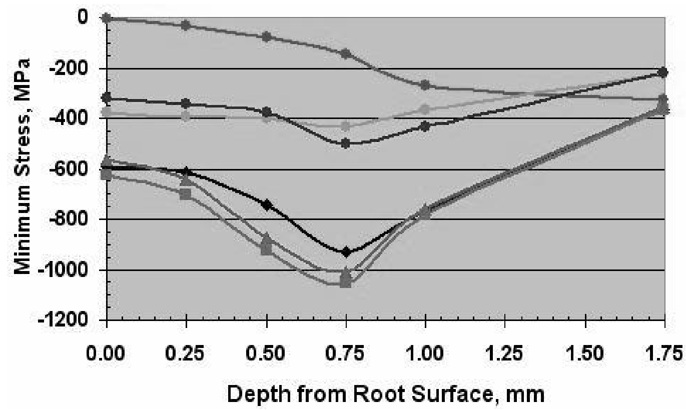


Figure 13. Evolution of minimum principal stress during the IQ process. The legend is given in Figure 11.

Stress State During Tooth Loading

The y axis of the fatigue data plot in Figure 7 shows both load and stress numbers. The load was the actual load applied by the machine. The stress was calculated using an AGMA equation.[2] The calculated stress is at the root fillet, and these levels are near the yield strength of the carburized layer. One might ask, "How can this be"? The answer is that the AGMA equation assumes an initial stress free condition, while the carburized and quenched hardened gear has residual surface compression.

Computer simulation was used to study the change in stress state at the tooth root during application of the bending load, with both an initial stress free condition and the residual compressive states of the OQ and IQ gears considered. Table 3 lists the maximum stress calculated for the root fillet under a tip load of 6228 N (1400 lbs) for the traditional AGMA method, a stress free finite element model, and finite element models that carry forward the residual stress state from the baseline OQ process route and the IQ process route. From the values in this table, the benefit of residual surface compression in reducing the maximum cyclic stress is evident. The benefit of the IQ process over the baseline OQ process is also evident by virtue of the lower maximum stress. Figure 14 summarizes the effect of tooth loading by showing the maximum principal stress state in the root fillet for the three finite element models – initially stress free, residual stress from the baseline OQ process, and residual stress from the IQ process. It is interesting that while the maximum principal stress for the OQ and IQ are nearly the same, under the bending load, they have separated and the stress in the IQ gear is lower. This lower stress accounts for the improved bending fatigue strength.

Table 3. Maximum Stress in the Root Fillet for a Tooth Tip Load of 6228N (1400 lbs.)

AMGA Method	FEA (no residual stress)	FEA (OQ Procees)	FEA (IQ Process)
1345 MPa	1600 MPa	1020 MPa	820 MPa

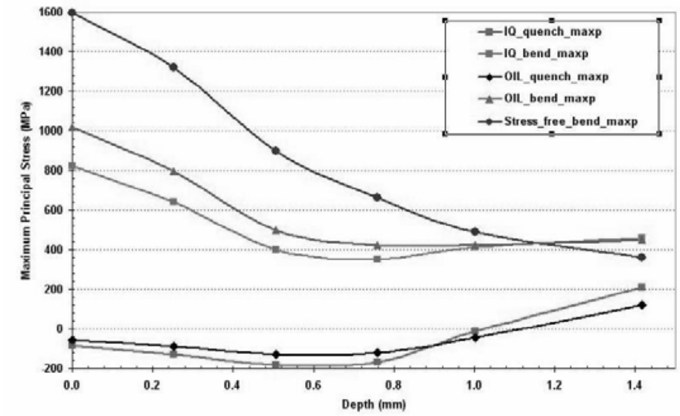


Figure 14. Maximum principal stress in the root fillet.

Summary

The major findings for this study include:

- Intensive quenching produced higher compressive surface stress than conventional oil quenching;
- Higher surface compressive stress improved gear tooth bending fatigue strength;
- Computer simulation was shown to accurately predict the final residual stress state and the dimensional changes due to heat treatment;
- Computer simulation provided a tool to investigate the metallurgical events that occur during heat treatment so that the origins of the final stress state, distortion and metallurgical phases could be better understood; and
- Gear stress calculations should include the effect of residual stress because without residual compressive stress, these test gears would have failed, not by fatigue, but by simple overload.

Much more work remains to be done to continue to improve the fatigue life of critically loaded parts such as gears, bearings and shafts by heat treatment and other processes such as shot peening, surface burnishing and laser shockpeening. Some immediate questions relate to the effect of the thickness or depth of the compressive layer in addition to the magnitude of compression, and the interaction between these processes.

Acknowledgements

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1. A.M. Freborg, et al., "Bending Fatigue Strength Improvement of Carburized Aerospace Gears", ASM-HTS, (2005)
2. D.W. Dudley, Handbook of Practical Gear Design, McGraw-Hill Book Company, New York, (1984)