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Residual Stress and Bending Fatigue Strength in Carburized and Quench Hardened Pyrowear 53 Steel Gears

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Abstract

Carburization of alloy steels promotes the formation of compressive residual surface stress upon quenching, and that compressive surface stress enhances fatigue life. To further investigate the role of residual stress on fatigue strength, a project was undertaken to assess the role of residual stress magnitude on bending fatigue life of a spur gear through innovative quenching and the achievement of deeper compressive surface stress. DANTE Solutions demonstrated the feasibility of improving the bending fatigue life of Pyrowear 53 steel gears by achieving deeper compressive residual stress in carburized and quench hardened parts. At the same time, concepts of integrated computational engineering (ICME) were employed for simulation of the steel heat treatment and then of the gear service stresses.

Computer simulations of two different quenching processes, conventional oil quenching and intensive quenching, were conducted using the DANTE heat treatment simulation software to predict differences in final residual stress state. Although similar hardness profiles were predicted for both processes, the predicted surface stresses at the center of the gear root were -600 MPa and -300 MPa, with the intensive quenching producing higher compression. These predictions agreed with XRD measurements. The stresses predicted at the tooth fillet were even more compressive and maintained similar separation between the two quenching methods. The simulations showed that timing and sequence of martensite formation that occurred during the quenching process was related directly to the magnitude of compressive residual surface stress.

Tooth bending fatigue tests, conducted by Gear Research Institute, showed an endurance limit difference of 15% between the two quenching methods, with higher surface compression yielding higher fatigue life. Scatter in the data was significant, even with surface conditions within product specification. Isotropic surface finishing increased the endurance limit, and the difference between quenching methods was maintained.

Introduction

Material and Process

Both the automotive and aerospace industries have a need to reduce weight and improve vehicle performance. For powertrain gearing this means increasing the power density of the transmission as weight is removed and performance is increased. Importantly, this must be done without degrading the service life of the components, and for gears that means that bending fatigue life and contact fatigue life must be improved. Several "new" gear steels have been developed toward this goal, each with improved strength and resistance to softening as operating temperatures have increased.[1,2] In helicopter transmissions, Pyrowear 53 steel, a patented alloy by Carpenter Technology Corp., has replaced AISI 9310 steel in many applications.

Pyrowear 53 is a carburizing grade of steel that was developed in the 1970's.[2] Its chemistry is given in Table I. Major characteristics of this steel are its high hardenability, its combination of high strength and toughness, and its ability to retain strength under loss of lubricant conditions. Pyrowear 53 provides an enhanced safety margin in comparison to carburized 9310 steel. As a result, it is used in many military applications where performance and safety outweigh cost considerations.

Table I. Typical Pyrowear 53 Steel Chemistry

Fe	C	Mn	Si	Cr	Ni	Mo	Cu	V
bal.	0.1	0.35	1.0	1.0	2.0	3.25	2.0	0.1

One issue with powertrain improvement is the time and testing required to substitute a new material and/or geometry into the drivetrain. The testing of a new component is costly and the time period can be excessively long. For this reason, many potential enhancements are shelved until entire new systems are being designed. Existing systems tend to remain as-is, even though potential improvements may be available. However, process modifications that use existing materials and geometries offer a path for improvement of existing systems at minimal time and cost. Heat treatment is one such process, since all gears rely on thermal processing to meet performance requirements. If a change in the heat treatment process can result in performance enhancement of the transmission components, then improved transmission performance can be realized without an expensive redesign and testing program. Since gear life is dependent on the nature and magnitude of surface residual stress, a specific goal of this study was improvement in the level of surface compressive residual stress. The technology applied was the use of intensive quenching in place of conventional immersion quenching in agitated oil to produce enhanced residual compressive surface stresses.

Prior research showed that a change in quench hardening practice from immersion quenching to intensive quenching could improve bending fatigue life.[3] Notched bars of Pyrowear 53 steel were carburized on one face and hardened conventionally or by intensive quenching, and then subjected to three point bending fatigue testing. The result was an improvement in cyclic bending life for the intensively quenched samples, and this was related to greater surface compressive stress as measured by X-RAY diffraction and also predicted by computer simulation.

Process Simulation

Before embarking on an experimental program of manufacturing and testing gears, computer simulation was used to investigate gas carburization and quench hardening processes in terms of residual stress. The DANTE software package was used for this task. Parameters specific for Pyrowear 53 steel were developed previously, so both carbon diffusion and phase transformations were modeled. The DANTE software is a set of user subroutines that link with commercial finite element solvers ABAQUS/STANDARD[1] and ANSYS Mechanical[2]. A database of mechanical, thermal and phase transformation properties for many carburizing and hardenable steels is part of DANTE, and this includes the Pyrowear 53 steel addressed in this study.

The structure of the DANTE software is shown in Figure 1. Inputs consist of component geometry, process schedule, and material data. The simulation calculations include carbon diffusion to get the carbon distribution in the part, and thermal, mechanical and metallurgical calculations to determine the phase fractions, temperatures, stress state, and dimensional changes in the part as heating and quenching takes place. The results include the local histories for stress, displacement, phase fractions and temperature, and the final hardness profile, residual stress state, and part dimensions.

Material data is critical to the accuracy of heat treatment simulation of steels, especially since the crystal structure and properties change significantly during the heating and cooling steps. The carbon gradient from carburization also results in significant property changes. For Pyrowear 53, the high hardenability results in austenite transforming to martensite during quenching, even at slow cooling rates. Figure 2 reports the martensite start temperature for different carbon levels as determined from dilatometric tests. Knowledge of when martensite forms is critical since the plastic properties for

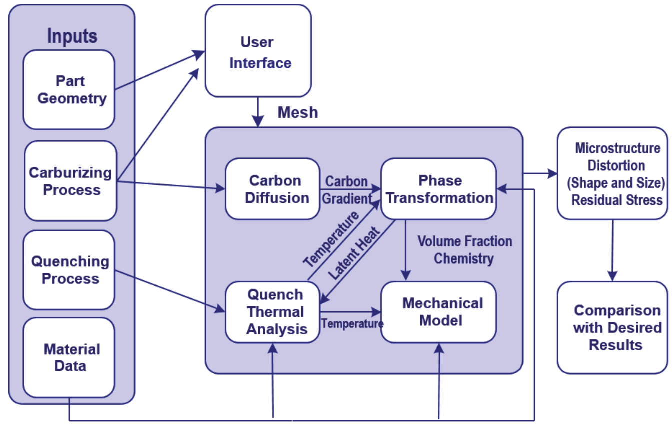

Figure 1: Flowchart showing the structure of DANTE calculations.

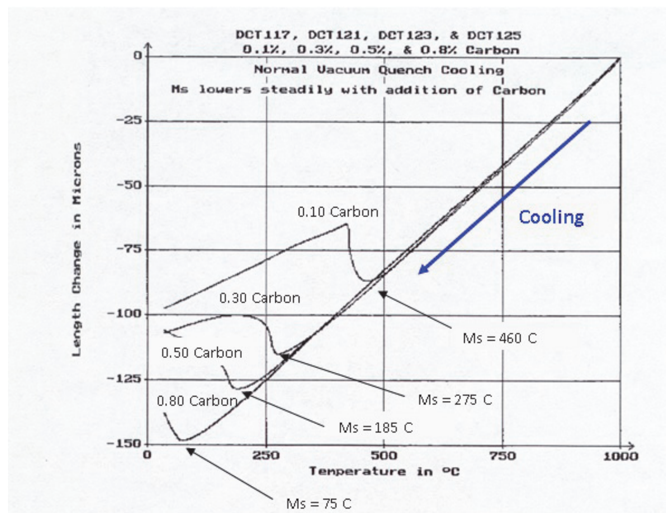

Figure 2: Martensite start temperature for carburized Pyrowear 53 steel.

martensite are so different from those of austenite. For accurate simulation of a quench hardening process, these data must be available.

Process data are also important to the accuracy of the heat treatment simulation. Especially important are the thermal boundary conditions such as the surface heat transfer during quenching. Because oil boils as heat is extracted from the racked parts, heat transfer changes as the part cools. The local agitation or flow of oil also varies around the part, so cooling is not uniform. Specific tests were not conducted to determine the heat transfer data for the gears used this study, so 'typical' values for oil quenching were used.[5] Figure 3 shows such a 'typical' data set for oil quenching.

For intensive quenching, the aim is to extract heat from the parts by using extremely fast flowing water so that no film boiling occurs, and even nucleate boiling may be absent. IQ Technologies, Inc. supplied heat transfer data for their process. A constant value of 30 kW/(m^2*C) was used. More recent work has reported values of 25 kW/(m^2*C) as being typical for intensive quenching.[6]

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[1] ABAQUS/STANDARD is a product of Dassault Systemes Simulia Corporation, Providence, RI, USA.
[2] ANSYS Mechanical is a product of Ansys, Inc., Canonsburg, PA, USA.

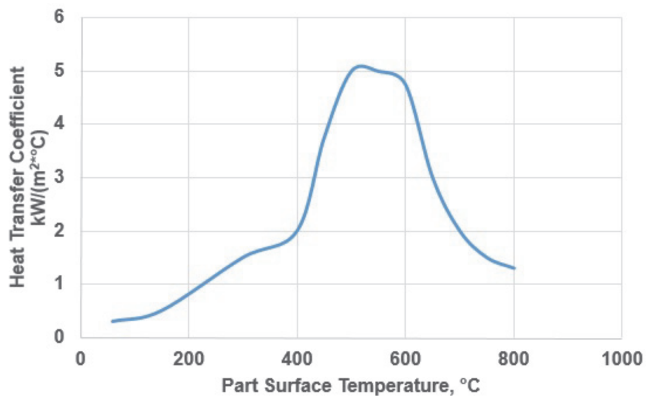


Figure 3: Surface heat transfer used for oil quenching of gears.[5]

Experimental Procedures

A total of thirty two gears were purchased from a helicopter OEM in the as-machined condition. These gears were machined from Pyrowear 53 bar stock and the geometry was specifically designed for single tooth bend testing. The gear has 40 teeth, a module of 2.54, and a face width of 6.35 mm.

Once received at our office, the gears were heat treated and then finish ground. Two quenching practices were followed while all other heat treatment steps were the same. The purpose of this was to produce different residual stress states in gears having the similar microstructures. The heat treatment steps are given in Table 2. All 32 gears were vacuum carburized in one batch; prior to carburization, the gears were copper plated so that only the tooth flanks and root were carburized. Figure 4 shows a view of one spur gear at a stage during its heat treatment processing. The copper plating was used to prevent carburization of some surfaces, and also to prevent decarburization during certain process steps. Sixteen gears were then hardened and tempered following the baseline schedule which used oil quenching, and the remaining gears were hardened and tempered following the intensive quenching schedule, see Table 2. After tempering, approximately 0.13 mm of stock was ground from the tooth faces of the oil quenched gears, and 0.18 mm of stock was ground from the intensively quenched gears. The aim was for the only process difference to be the quench step, so the effect of grind stock differences was investigated using simulation prior to proceeding with finish grinding.

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

	Baseline OQ Process	IQ Process
Vacuum Carburize	8 hours at 927° C	8 hours at 927° C
Subcritical Anneal	2 hours at 635° C	2 hours at 635° C
Austenitize & Quench	913° C, quench in oil at 66° C	913° C, intensive quench to 20° C
Deep Freeze	1 hour at -73° C	1 hour at -73° C
Double Temper	2 hours at 232° C	2 hours at 232° C

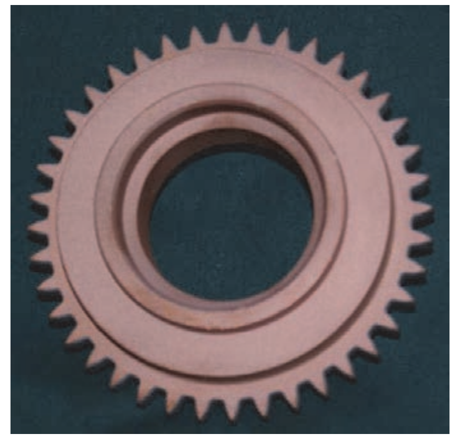


Figure 4: Spur gear used for bending fatigue test.

Heat Treat Process Simulations

Heat treat process simulations were conducted to predict the levels of residual stress and dimensional changes that could be expected from both processes before green gears were procured,. This was a necessary task as the amount of growth due to heat treatment was not known, the difference in growth between the two quenching methods was not known, and there was concern that differences in finish grinding could remove any residual stress differences between the two processes. These simulations proved to be extremely useful, as explained below.

A single tooth sector of the gear was meshed using hexahdral elements, also known as brick elements. Figure 5 shows the meshed tooth sector, with a manified view of the tooth and root cross section. The mesh density is higher along surfaces in order to capture the carbon gradient and the steep thermal and stress gradients that develop during quenching.

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 6. These predicted data sets were extracted from a 3D model of the gear. While the green dimensions were unknown to us, the final dimensions and the typical amount of finish grind stock, 0.005 inches (0.13 mm), was provided to us. The models predicted the amount of growth expected for the two process routes, and the residual stress states after hardening and before finish grinding could be compared. It 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

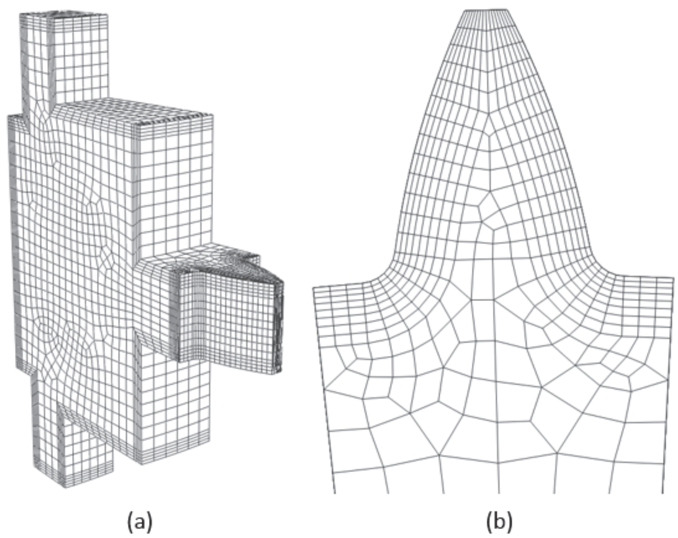


Figure 5: (a) Hexahedral mesh developed for a section of the spur gear. (b) Magnified view of the mesh in the tooth and root.

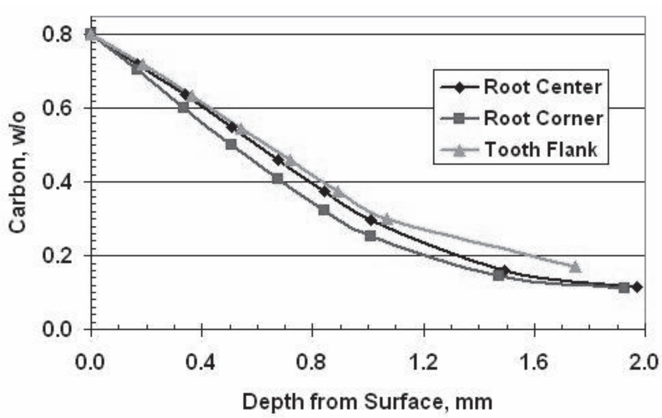


Figure 6: Carbon profiles at the indicated locations.[4]

information to the study, and simulation provided the method to answer this question.

Using the DANTE software, it was determined that a baseline gear would grow approximately 0.033 mm (0.0013 inches) per side and the IQ processed gears would grow approximately 0.076 mm (0.003 inches) per side, or 0.043 mm (0.0017 inches) more than the baseline gears, see Figure 7. This meant that the standard (0.005 inches) would be ground from the baseline gears and that 0.18 mm (0.007 inches) of stock would be ground from the intensively quenched gears.

The same simulations predicted the residual stress states that would be produced by the two quench hardening processes. These are shown in Figure 8, as are the depths of stock to be removed. From Figure 8, it is clear that the simulations predicted that the IQ route would produce a significant increase in residual compression over the baseline process.

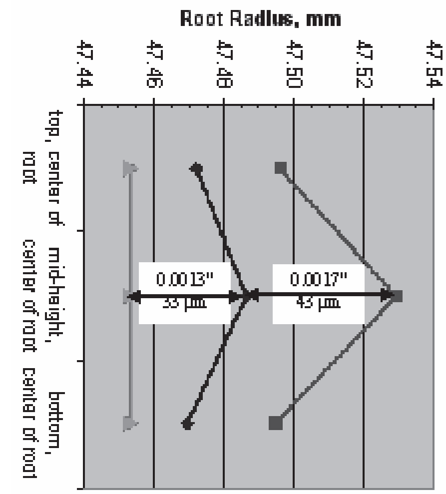


Figure 7: Radial location of the gear root, showing the initial or green location(▸), and the heat treated locations for the baseline (◆) and IQ (■) processes.[4]

The compressive field in the IQ processed gear was predicted to extend deeper into the gear body than that of the baseline gear. These predictions showed that even with the anticipated difference in stock removal that a significant difference in residual compression would exist after finish grinding.

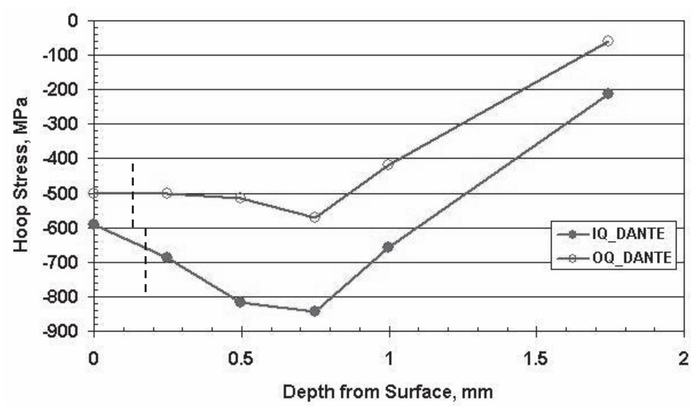


Figure 8: Predicted residual hoop stress at center of tooth root for the baseline and IQ processes. The grinding stock removal is indicated by the dashed lines.[4]

Figures 9 and 10 examine the model predictions in more detail by looking at data at specific locations over the course of the quench. Figure 9(a) identifies two locations associated with the root fillet, one at the surface and the other one at 1.25 mm from the surface. The carbon level at the surface is 0.65% and in the sub-surface location is 0.20%. Figure 9(b) shows that the surface cooling rate is slightly faster than that at the sub-surface point. There is a predicted temperature drop during the air transfer from the furnace to the quench tank, as indicated by the graph in (b) for the15 second period before the quench starts. The sub-surface location starts to form martensite at less than 10 seconds of quenching, which is over 30 seconds earlier than the surface location, and that sub-surface martensite formation is quickly completed in ~20 seconds. At 150 seconds of quenching, the surface martensite transformation has been active for over 100 seconds but is still only 70% completed.

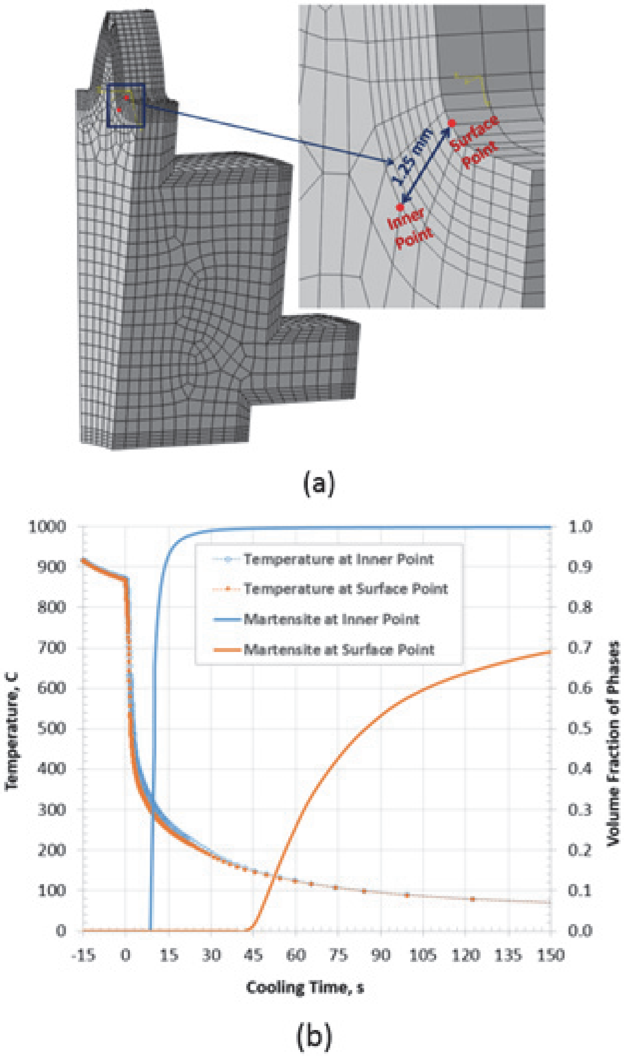


Figure 9: Response of gear root fillet during quenching: a) surface and inner points selected, and b) relations between temperature and martensite transformation at the two selected points.

This difference in the timing of the phase transformation has a significant effect on stress evolution. Figure 10 shows the stress histories for these same locations. It is clear from both (a) and (b) graphs that several stress reversals take place. The first stress reversal is due to the thermal gradient between the surface and sub-surface, and it occurs while both locations are fully austenitic. The next stress reversal occurs when the sub-surface is transforming to martensite and the surface remains austenite. The final stress reversal occurs when the sub-surface has completed its transformation to martensite and thermal contraction of the gear body pulls both the sub-surface martensite and surface austenite in compression. As the gear body continues to cool and transform to martensite, the sub-surface stress rebounds as the core expands, but the surface stress continues to become more compressive. The volumetric expansion of the surface as martensite forms is restricted by the already transformed sub-layers, and this is the contributor to surface compression. At the end of quenching process, high magnitude of residual compression is predicted at the surface point, and low magnitude of compression is predicted at the specific subsurface point. In regions deeper than this specific sub-surface point, tensile residual stress is predicted.

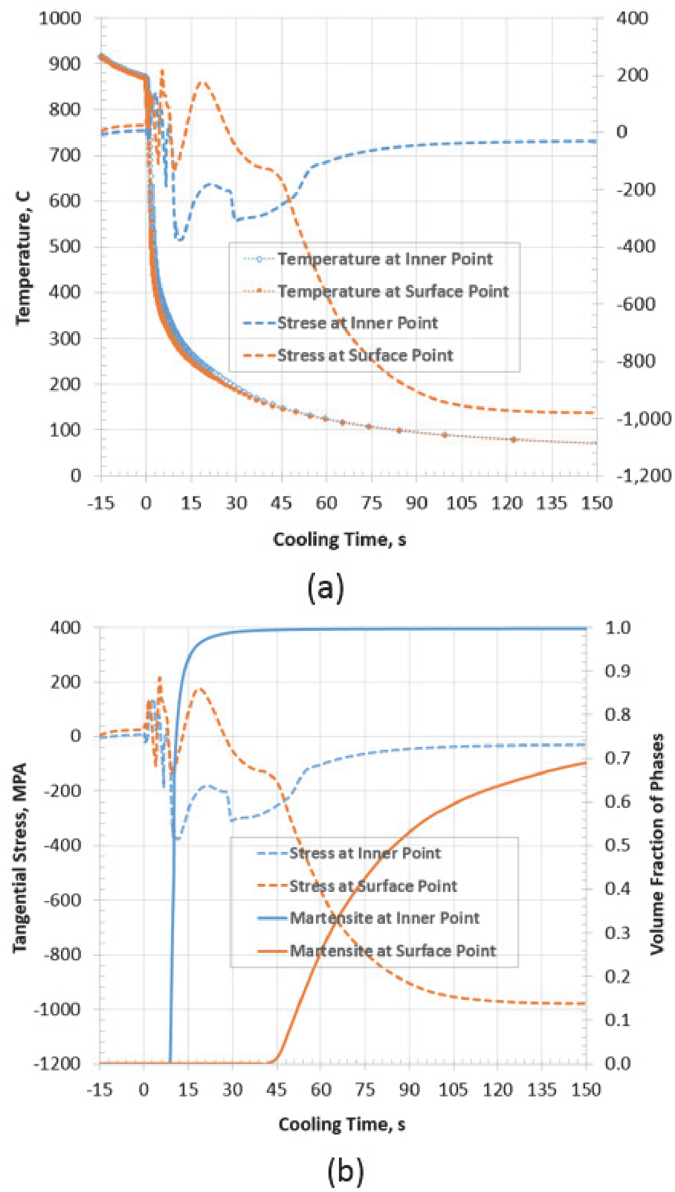


Figure 10: Response of gear root fillet during quenching: a) relations between temperature and tangential stress, and b) relations between temperature and martensite transformation at the two selected points.

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.

With the high hardenability of Pyrowear 53, the microstructures for both quenching methods were tempered martensite in the carburizied case and core of 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, even accounting for surface grinding; values ≥ HRc 60 were measured on witness bars. The core hardnesses were HRc 42 for both gear sets.

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 11. 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 for complicated geometric locations such as a gear root. The scatter band for both processes approach 100 MPa (14.5 ksi). The two XRD data sets for each gear are measured from opposite root positions.

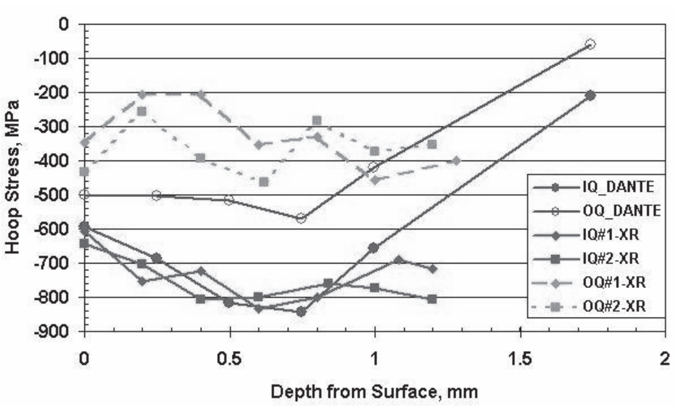


Figure 11: Hoop stress profiles at the center of the root for OQ and IQ gears as predicted by computer simulation and calculated from XRD measurements.[4]

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. The direction of the minimum or most compressive principal stress was tangential to the gear tooth/root surface. This is significant because this is the typical cracking location for bending fatigue failures. For the OQ gear, the minimum principal stress at the surface of the root fillet location was predicted to be -600 MPa (-87 ksi), while the predicted minimum principal stress for the IQ gear was -820 MPa (-118.9 ksi). The maximum principal stress at this location was predicted to be -30 MPa (-4.4 ksi) for the OQ gear and -60 MPa (-8.7 ksi) for the IQ gear.

Single Tooth Bending Fatigue Testing

The gears were tested at Gear Research Institute which is located at Pennsylvania State University in State College, PA, using a servohydraulic testing machine with a specially designed fixture to apply a cyclic bending load to two teeth. A schematic of the fixture is shown in Figure 12. 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 turned 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 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.

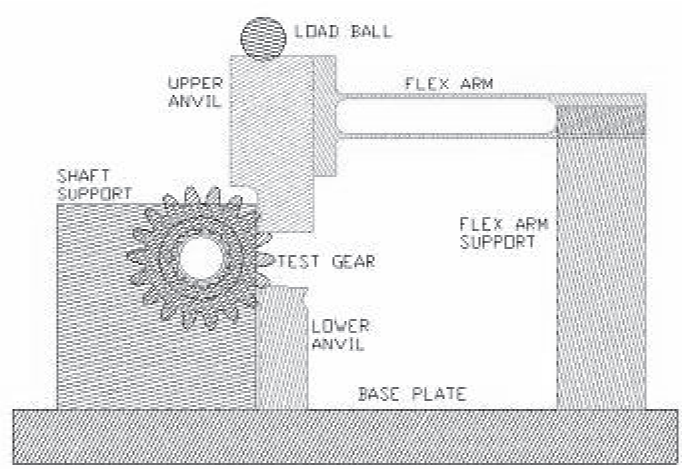


Figure 12: Schematic of tooth bending fatigue fixture at Gear Research Institute.

The fatigue test data for the OQ and IQ gears are shown in Figure 13. Qualitatively, the IQ gears have higher tooth bending 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. The IQ gears have approximately a 15 % improvement in life over the baseline OQ gears.

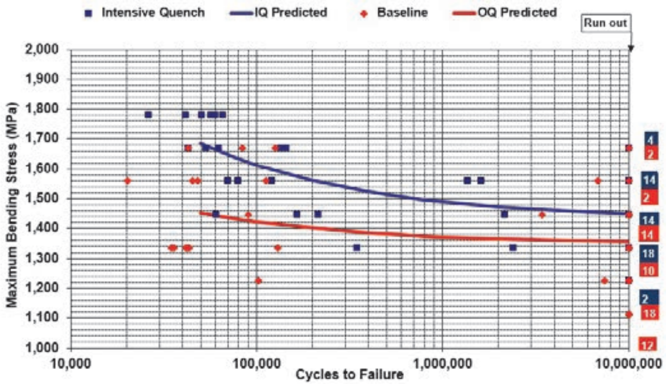


Figure 13: Single tooth bending fatigue data.

Service Stress

The study showed that increased residual surface compression in the gear root resulted in improved bending fatigue life. In this case, intensive quenching was used to produce a higher magnitude of compression than the baseline oil quenching. A higher magnitude of residual surface compression produced higher fatigue strength for parts having similar microstructures and hardness levels. Questions exist as to whether this translates to better rolling contact performance for these gears. Gear failure includes more than just bending failure, with spalling also being a major issue. To investigate stress states further, a dynamic model was developed where gears were contacted under load while being rotated. The residual stress state from quench hardening was the starting stress state. This approach to modeling is an example of ICME where the effects of material processing on microstructure and properties are carried forward to applications so that service stress state can correctly account for a non-neutral starting condition.

The root experiences cyclic stress during the single tooth bending test, and since the test was conducted with a stress ratio of 0.1, tension is always present. During loading under rotation, the same root location goes through a somewhat different stress cycle, with tensile loading being the high magnitude as in the bending test. In both cases, the benefit of initial residual compression on the local root stress is apparent. The initial compressive stress decreases the stress realized during service and this is the reason for improved bending fatigue life.

The bending stress assuming an initial stress free condition was calculated using the finite element method and is shown in Figure 14. The position of tooth loading is indicated to be near the tooth tip. As expected, the maximum tensile stress of almost 1600 MPa (232 ksi) is predicted to occur on the surface of the root fillet. Figure 15 is for the same finite element model except the residual stress state from the OQ heat treatment is included as the initial stress state. Now, the maximum tensile stress at the root fillet position is reduced to 1110 MPa (161 ksi) because of the initial compressive residual stress. Because a subsurface crack is more difficult to generate than a crack that starts on the free surface, fatigue resistance is improved. The maximum principal stress under bending load

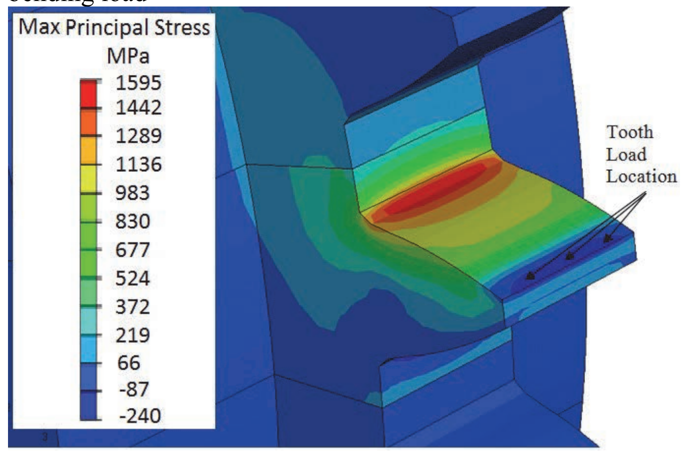


Figure 14: Maximum principal stress plot for tooth bending model with a stress free initial state.

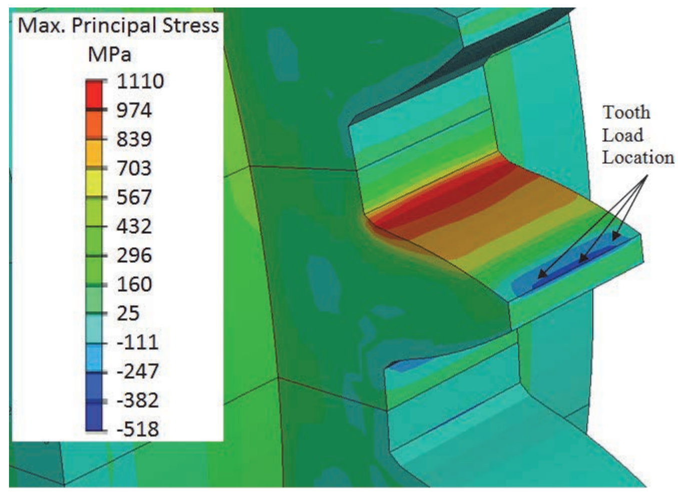
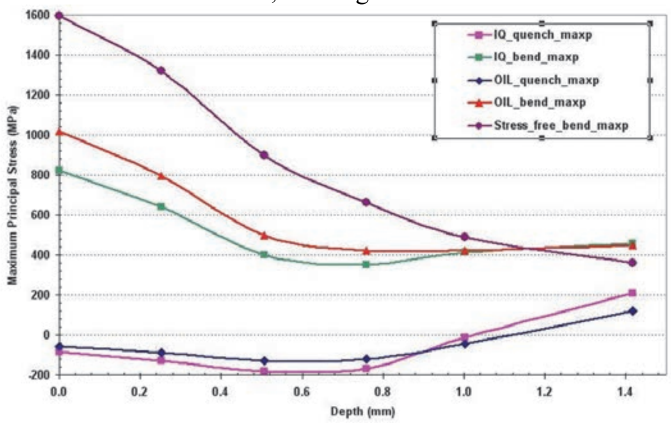


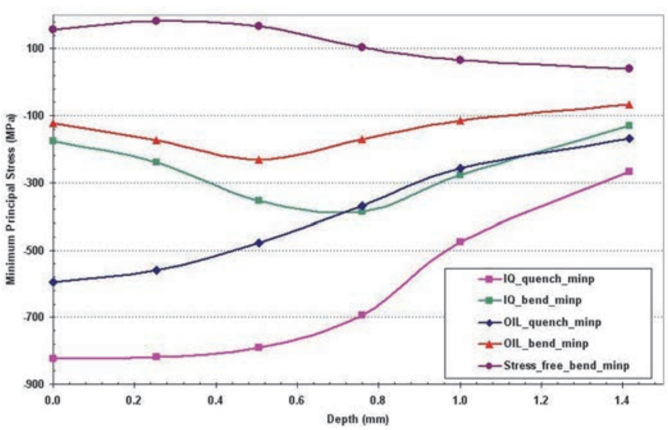
Figure 15: Maximum principal stress plot for tooth bending model accounting for initial residual compressive surface stress state.

is even less for the IQ gear because of even deeper compressive residual stress at the root fillet. This is shown more quantitatively in Figure 16(a) where maximum principal stress is plotted as a function of depth from the fillet surface. Figure 16(b) shows the calculated minimum principal stress for these three cases of different initial residual stress. For the stress free condition, not only is the maximum stress the highest, but the minimum principal stress is also tensile. Clearly the benefit of the residual compressive surface stress in the carburized case on the bending stress is evident. This residual surface compression allows the gear to carry a bending stress that approaches the yield strength of the alloy without actual yielding occurring.

The flank area at the pitch diameter experiences compressive loading from the mating tooth, but also frictional loading due to the rotation as sliding occurs between the teeth. The direction of the shear stress due to friction and sliding is opposite on each side of the contact point. Now the role of surface compression is conflicted as it does not affect the level of shear stress. However, the magnitude of surface



(a) Maximum Principal Stress



(b) Minimum Principal Stress

Figure 16: (a) Maximum principal stress and (b) minimum principal stress vs depth from the root fillet surface for finite element models with and without residual compressive surface stress due to carburizing and quench hardening.

compressive stress does retard cracking, so it should benefit resistance to spalling. While this was not directly tested in this study, another study on rolling contact of other carburized steels did show that surface compressive stress magnitude related to resistance of spalling.[7]

Summary

Gear tooth bending fatigue life is certainly improved by achieving higher magnitudes of surface compressive stress. For the carburized Pyrowear 53 steel and this gear geometry, intensive quenching produced deeper surface compressive stress than oil quenching and higher resistance to bending fatigue.

Accurate process modeling was used in this study to demonstrate that oil quenching and intensive quenching would produce the desired difference in residual stress states. Accurate material data were available in the DANTE material database for Pyrowear 53 steel so that this modeling could be confidently conducted.

Simulation of gears in service requires that the stress state resulting from prior processing, including heat treatment, be taken into account.

Further study of dynamically loaded gears is recommended to investigate the role of initial stress state on service stress and subsequent life. If bending fatigue is a limiting condition, then increased surface compression will definitely help gear life.

Acknowledgments

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