Improving the Bending Fatigue Strength of Carburized Gears

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Abstract

One of the ongoing development objectives of the US Army Aviation Applied Technology Directorate is to improve the power density and gear life for helicopter transmissions. If the fatigue lives of currently employed gear designs can be improved through innovative manufacturing processes such as advanced heat treatment techniques, costly redesign can be avoided. This paper reports on a Phase I SBIR project sponsored by the US Army, with the goal being a 25% improvement in the bending fatigue performance of carburized Pyrowear 53 steel gears. This Phase I project included a combination of process simulations and physical experiments, with the material quenching process being the primary variable examined as a means of achieving the project goal. In lieu of making and testing gears, a notched test bar was designed for testing in cyclic 3-point bending to simulate cyclic stresses in the root of a gear. The DANTE® heat treatment simulation software was used to predict residual stress levels in carburized notched-bar test samples that were either conventional oil quenched or intensively quenched after austenitization. Physical test samples were then machined, carburized and heat treated, with subsequent calculation of residual stress from X-ray diffraction measurements and microhardness measurement to document the differences in these values due to heat treatment. Three-point bending fatigue tests were then conducted to determine the fatigue performance improvement that was feasible due to innovative quenching. Process simulation accurately predicted enhanced residual surface compression achieved through the intensive quenching, as well as the sample hardness profiles. This paper presents data to characterize Pyrowear 53 alloy for heat treatment simulation, a discussion of the simulation and physical testing of the carburized and heat treated test samples, and the results of the bending fatigue tests.

Background

Overview

The steel alloy Pyrowear® 53 is being increasingly used in helicopter transmission gear applications for the US Army, based primarily on its resistance to tempering at high temperatures and excellent fatigue strength. These attributes are critical in attack helicopter applications, where the transmission assembly is required to function under severe conditions wherein loss of gear lubrication can occur. The assembly must be able to operate without breakdown for a 30 minute time period in the absence of internal lubrication or cooling, and thus the need for a highly temper resistant alloy.

Pyrowear® 53 has a unique alloy content, as indicated in the alloy chemistry data presented in Table I.

TABLE I.
Pyrowear® Alloy 53 – Base Composition

Carbon	Mn	Si	Cr	Ni	Mo	Cu	V
0.10	0.35	1.00	1.00	2.00	3.25	2.00	0.10

The alloy content for this material is specifically designed to achieve resistance to softening at high temperatures and retain hot hardness in the carburized case, while maintaining high core impact strength and fracture toughness.

A variety of innovative processing techniques continue to be advanced to enhance material performance through manufacturing, processing and finishing. For applications where part life is limited by fatigue, significant life enhancement can be realized by introducing compressive stresses in the part surface, and by eliminating stress concentration factors.
Of primary interest in this project was the investigation and application of a novel heat treatment process called Intensive Quenching® to facilitate enhanced residual surface compressive stresses with consequent material fatigue life improvement. [1,2,3] Developed by Dr. Nikolai Kobasko, the Intensive Quenching (IQ) process is an alternative way of quenching steel

parts to achieve deep residual compression in part surfaces. The technology is based in-part on the achievement of a large thermal gradient in the part by rapid surface cooling. In non-carburized parts, the process has been shown to provide an extremely rapid and uniform transformation to martensite in the part surface layers while the core remains austenitic. This condition creates a very hard shell on the part that is under a state of deep compression. As the hot austenitic core cools and thermally contracts, the level of surface compression is deepened. When the core subsequently transforms from austenite and expands, there is some reduction in the level of surface compression, but the final level of surface compression in the IQ treated components remains much higher than that of conventionally quenched components.[4,5,6,7]

For this program, the premise for adapting this technology to carburized Pyrowear 53 was explored, with goal of achieving comparable or improved surface compression enhancement as witnessed in non-carburized material. While carburization is designed to maintain surface compression during heat treatment by delaying formation of surface martensite, the potential for intensive quenching to foster additional enhancement was a key factor of investigation.

Material Characterization for Heat Treatment Analysis

Proper mechanical and kinetics material property data are critical to the accurate application of any simulation technology to process modeling. For heat treat simulation, the required mechanical characterization includes material stress-strain behavior by phase over the range of stain rates and temperatures encountered during a given heat treat process. Linkage with a corresponding kinetics model for material phase transformations then provided the general capability for the overall material model. The heat treatment simulation software DANTE® links both the mechanical behavior model and the phase transformation kinetics models to accurately predict the material response to heat treatment, specifically with respect to metallurgical phase volume fraction, residual stress, and distortion.[8,9,10] In defining material behavior, DANTE's material model incorporates both rate dependent and independent yielding, kinematic hardening and recovery, and isotropic hardening and recovery – all as functions of temperature and metallurgical phase. However, the mechanical properties and the kinetics must be properly characterized to supply the DANTE® material models with the data necessary to achieve accurate results.

The function of the kinetics model is to define the phase transformation behavior of the given steel within the heating and cooling temperatures and rates of the process. For the DANTE software, a complex set of differential equations is used to describe the phase transformation kinetics behavior for both diffusive (i.e. austenite formation or austenite decomposition to ferrite, pearlite, or bainite), and non-diffusive (i.e. austenite decomposing to martensite) transformation processes. This set of equations is then coupled with the equations governing the mechanical and thermal behavior of the material being subjected to the process scenario under consideration. Mechanical property data for the carburized Pyrowear 53 material were obtained by tensile and compression tests conducted at a variety of strain rates and temperatures, for varying carbon levels. [11]

Phase transformation data for the kinetics models are obtained principally by dilatometry. For the Pyrowear material, samples were through-carburized to four carbon levels (0.1, 0.3, 0.5 and 0.8 percent by weight), and then provided to Oak Ridge National Laboratory for testing using their high speed quenching dilatometer.

Typically, steel phase transformation kinetics are most commonly presented in the form of Time-Temperature-Transformation (TTT) or Continuous Cooling Transformation (CCT) diagrams. For the subject Pyrowear material, Carpenter Technology Corporation was able to provide the simple TTT diagram and critical temperatures shown in Figure 1.

Critical points

Critical Point	Core		Case	
	°F	°C	°F	°C
A_c1	1505	819	1340	727
A_c3	1605	874	1455	791
M_s	950	510	265	130
M_f	675	357	-155	-104

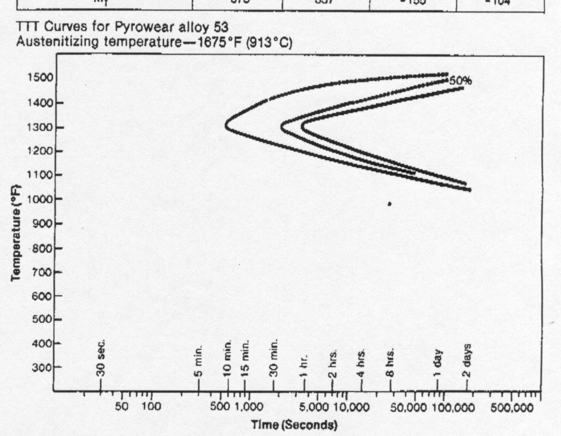

Figure 1. TTT and Critical Temperature Data for Pyrowear 53 Steel Reported by Carpenter Technology Corporation.[12]

From this simple figure several important heat treating characteristics of Pyrowear 53 are evident. Most prominent is that the steel is highly resistant to diffusive phase transformation, with the ferrite/pearlite nose located at 15 minutes at 704° C (1300° F). With a specified core martensite start temperature of 510° C (950° F), and associated carburized case martensite start temperature of 130° C (265°F), the material has excellent hardenability. Consequently, phase transformation kinetics characterization focused primary on the non-diffusive martensitic transformation.

As an example of the type of dilatometric phase transformation data obtained for the Pyrowear material, general results from 0.8%C (carburized) and 0.1%C (baseline) specimens are shown in Figures 2 and 3. For the 0.1%C material, an isothermal hold at 500 ºC, which is below the martensite start temperature (Ms) of 510 ºC reported by Carpenter Technology Corporation, and well below the reported ferrite/pearlite nose temperature of 700 ºC did not result in any austenite decomposition and martensite formed upon subsequent cooling.

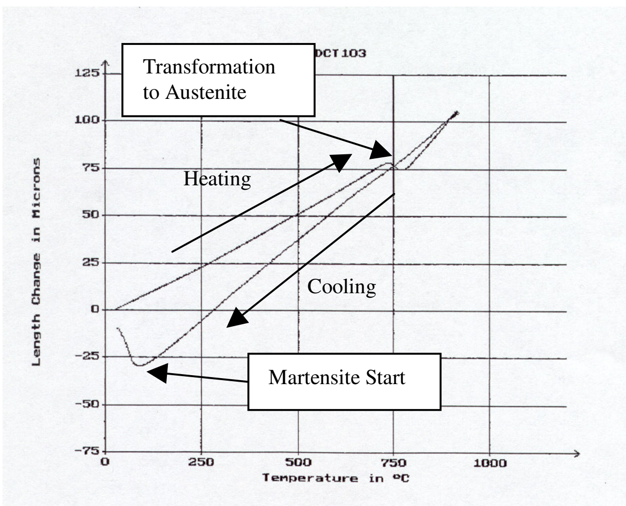

Figure 2. Dilatometry for 0.80% C Pyrowear Sample.

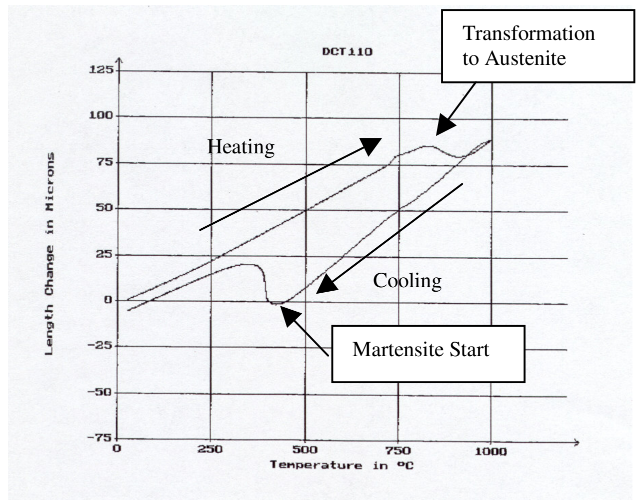

Figure 3. Dilatometry for 0.10% C Pyrowear Sample.

With completion of the Pyrowear dilatometry work, the data were used to provide the DANTE simulation software with the necessary parameters for prediction of Pyrowear phase transformation behavior. Sound material data, linking mechanics with phase transformation predictive capability, is essential for accurate implementation of simulation technology to process modeling. The robust design of the DANTE material constitutive model, coupled with the detailed Pyrowear 53 material characterization data, provided a solid foundation for the process simulation work required in this project.

Analysis and Testing Program

<u>Objectives and Testing Program</u>

The primary objective of the Phase I effort was to demonstrate the potential for improving the bending fatigue strength of Pyrowear 53 steel used for helicopter transmission gears by heat treatment. The Army's Rotorcraft Force Modernization Fleet requires a substantial increase in main gearbox power density, with minimal impact on the gearbox interface. In lieu of redesigning gears and increasing gearbox size and transmission weight, this Phase I project focused on achieving these higher power density requirements through application of an innovative heat treating process. To achieve this objective and demonstrate technical, engineering and commercial feasibility for the innovation, an evaluation program was compiled consisting of a combination of process simulation and physical experiments. The principal goal was to establish two independent material populations based solely on differences in heat treatment, with simulation, physical testing and bending fatigue evaluation used to characterize improvement, based principally on the effect of enhanced residual surface compressive stresses. To this end, twenty-five kg (55 lbs.) of 60.3 mm (2 3/8") diameter Pyrowear 53 bar stock was donated from DCT's inventory. A general processing and testing program for the material was established, as summarized in Table II.

TABLE II.
Proposed Pyrowear Test Matrix

Process Route	Heat Treatment	Surface	Bending Fatigue	Metallography	Residual Stress
1	Oil Quench	Polished	18 Samples Available for Test	Microstructure, Microhardness	X-Ray
2	Intensive Quench	Polished	18 Samples Available for Test	Microstructure, Microhardness	X-Ray

Sample Processing and Preparation
Rectangular test bar blanks were machined from the bar stock with the length of the test bar being coincident with the bar stock rolling direction. In discussion with gear engineering experts at the Army Gear Research Laboratory at NASA-Glenn and Bell Helicopter, a modified "V" notch geometry for the 3-point bending fatigue sample was defined; this notch geometry was consistent with the notched flexure fatigue specimens used by Bell Helicopter. The modified "V" notch is a 60º included angle with a 1.16 mm raduis (0.0455") to simulate a typical gear tooth root geometry. The test specimen configuration is shown in Figure 4.

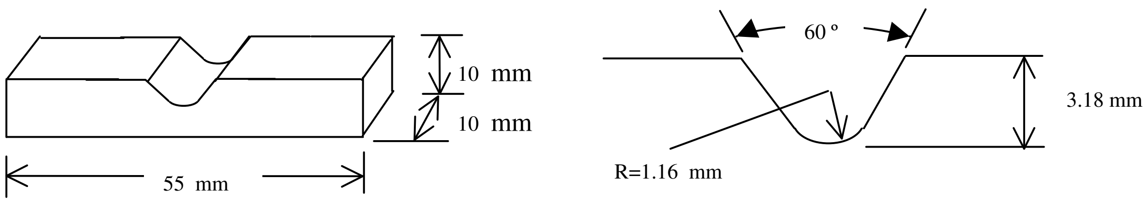

Figure 4. Modified "V-Notch" Sample Configuration.

To most accurately capture the combined carburizing and geometry effects of a Pyrowear gear, the notched test bars were carburized only on the top surface (including the notch), as shown schematically in Figure 5. To accomplish the localized carburization, the sides and bottom surfaces of the bending fatigue samples were masked with copper plating. This is standard practice for blocking carburization of selected surfaces on aerospace parts.

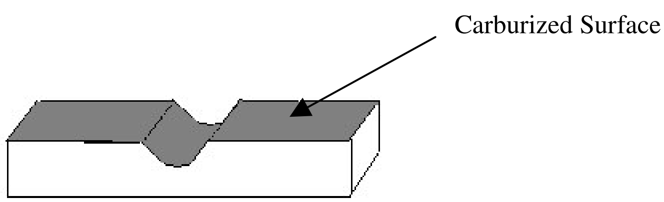

Figure 5. Schematic of Bending Fatigue Test Sample showing Orientation of Carburized Surface.

Results

Process Simulation
In preparation for heat treatment of the Pyrowear 53 test samples, a series of thermal/stress models was run to characterize the respective heat treating processes applied to the test pieces. The use of a simulation tool provides a rapid, non-destructive and cost effective means of assessing both the internal metallurgical behavior during and after processing, as well as the mechanical response, in terms of residual stress, hardness, and dimensional change. For this task, the heat treatment simulation software DANTE® was used to characterize the carburization and two quench hardening processes selected for this development program.

Carburization Simulation Results The Pyrowear 53 material was carburized to a carbon level of 0.80% and an effective case depth of 0.5 mm. The DANTE® simulation employed a carburization cycle with applied carbon potential as prescribed directly from the gear OEM's. The 3-D mesh for the simulation is shown in Figure 6, with the predicted profiles at both the notch and flat areas shown in Figure 7.

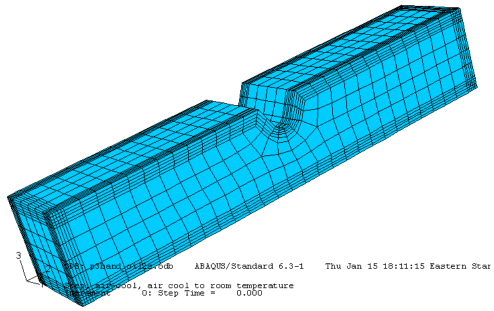

Figure 6. 3-D Finite Element Mesh of Sample For Process Characterization.

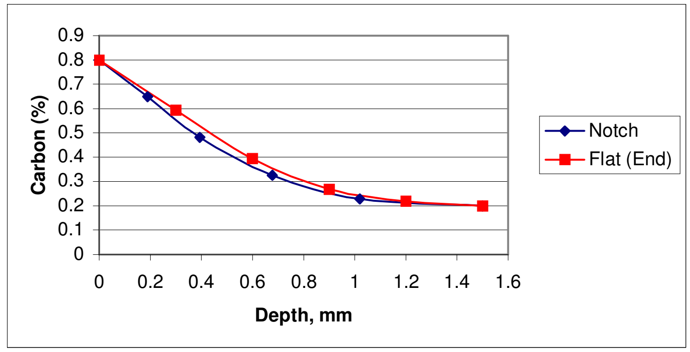

Figure 7. Predicted Carbon Profiles in Notch Bar Sample at both Notch and Flat Areas.

The plot in Figure 7 shows an important physical phenomenon with respect to the influence of part geometry on carbon diffusion behavior. The geometry at the root of the notch acts to disperse the carbon over an area, thus reducing the equilibrium carbon content slightly at intermediate depths, as compared with the flat carbon regions where the diffusion path is lineal.

Quench Simulation Results Simulations were also performed to assess the probable effects and differences in residual stress and hardness effects between oil and intensive quenching processes. Table III summarizes the process steps involved in each of the evaluated quenching operations after carburization. Simulation of the quenching was performed through application of heat transfer coefficient parameters for the oil, intensive quenching, and cryogenic processes. The DANTE® tempering model was also employed for the temper operation. Predictions of hardness and residual stress are compared against measured values in the next section.

TABLE III.
Phase I Pyrowear 53 Material Process Routing for Bending Fatigue Assessment

Process Route	Heat Treatment
1	Baseline Oil Quench Hardening: ♣ Austenitize 912° C (1675° F) ♣ Quench in Oil at 82° C (180° F) ♣ Deep Freeze (liq. Nitrogen at • -79° C (–110° F) for 1 hour) ♣ Temper at 232° C (450° F) ♣ 2nd Temper at 232° C (450° F)
2	Intensive Quench Hardening: ♣ Austenitize 912° C (1675° F) ♣ Intensive Quench in High Velocity Water ♣ Deep Freeze (liq. Nitrogen at • -79° C (–110° F) for 1 hour) ♣ Temper at 232° C (450° F) ♣ 2nd Temper at 232° C (450° F)

Physical Characterization

Microhardness Upon completion of the heat treat treatments on the Pyrowear notch bar specimens, microhardness profiles were measured at the sample notch, beginning at a depth of 0.005" (0.13 mm). A plot comparing the resulting hardness profiles for the two heat treatments is presented in Figure 8; also included are the hardness profiles predicted by the heat treat simulations. Here one sees the most pronounced improvement in hardness at the surface and subsurface to a depth of about 0.5 mm (0.02").

Residual Stress Both a conventionally oil quench and an intensively quenched notched bar sample were sent to Lambda Research for surface and internal residual stress characterization. A combination X-ray diffraction / chemical etching technique was used to measure lattice strains and then calculate the longitudinal residual stress as a function of depth from the notch root for each heat treatment. X-ray measurements were taken at 0.2 mm (0.008") increments, to a depth of 1.2 mm (0.047"). The simulation results and the measured test results display excellent agreement, as shown in the comparative plot presented in Figure 9. The project methodology has also shown the value of process simulation in predictive design.

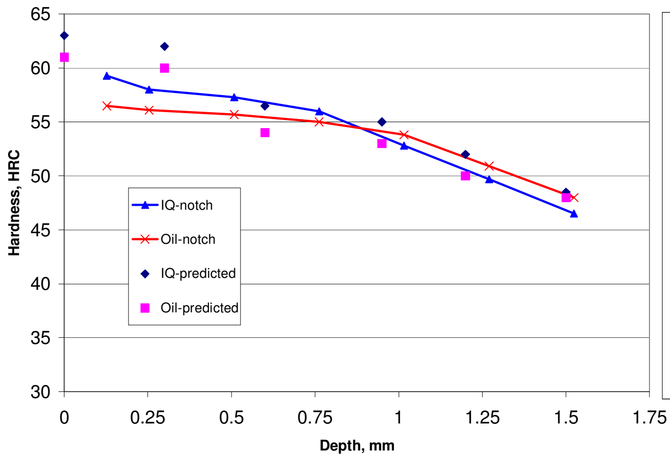

Figure 8. Measured and Predicted Microhardness Values for Oil Quenched and Intensively Quenched Test Bars as a Function of Depth.

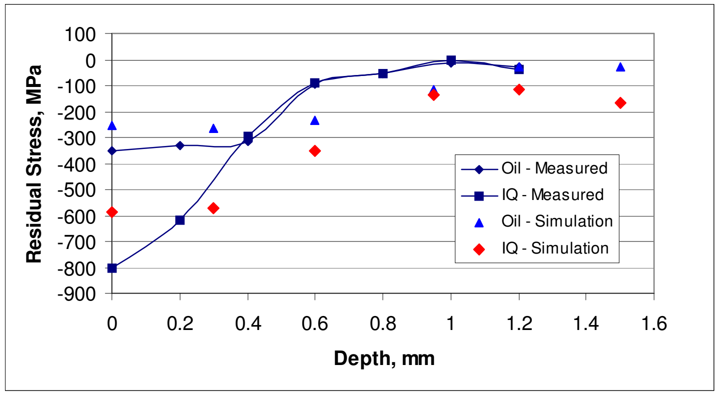

Figure 9: Predicted vs. Measured Residual Stress Profiles at the V-Notch as a Function of Depth.

The general results show that the IQ material is on the order of 450 MPa (65 ksi) more compressive at the surface than the oil quenched material, with minimal difference in microhardness.

Bending Fatigue Testing To assess the bending fatigue resistance of the carburized and heat treated Pyrowear 53 notch bar samples, three-point bending fatigue tests were conducted using a servo-hydraulic testing machine at Case Western Reserve University. The machine was operated using load control, with the minimum to maximum load ratio being 0.1 so that the notch was under constant cyclic tension. This condition assured that no slippage or sample movement occurred during testing, at least up to the point of large ram displacement due to cracking. To stop the test at or near crack development, strain gages were applied to the samples at the notch root. Figures 10 shows a photograph of an instrumented test sample, with the crack detection sensors applied across the notch.

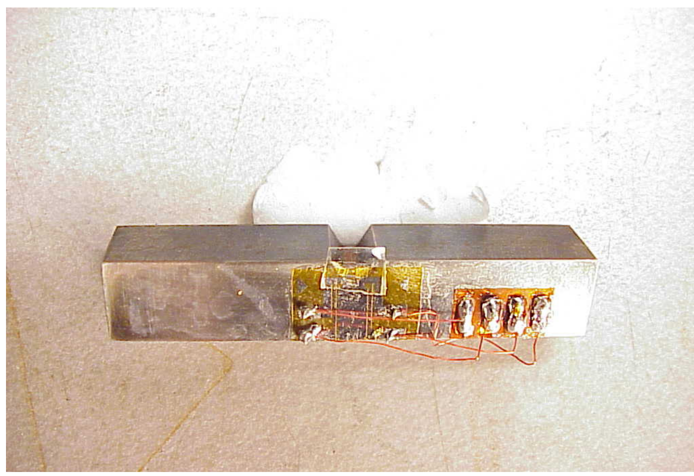

Figure 10: Instrumented Bending Fatigue Test Sample

Eighteen oil quenched and seventeen intensively quenched fatigue samples were tested in bending fatigue to compare the effect of the two heat treat processes on the resulting fatigue resistance. Figure 11 shows the resulting fatigue test data for the two quenched conditions. A test was stopped after the number of cycles exceeded 10^6 and declared a runout. Rupture of the strain gage occurred when a crack began to extend, and the test machine would automatically stop and the sample was declared a failure. Failed samples were bent, not broken. While there is scatter evident in the data, it appears that the resistance to bending fatigue is higher for the intensively quenched test bars than for the conventionally quenched oil test bars.

Statistical analysis of the data was performed to verify the apparent improvement in bending fatigue resistance due to intensive quenching was real.[13] Following a relationship used to compare the bending fatigue strength of gear teeth, raw data were transformed to allow comparison of projected lives at a normalized load. In this case, the normalized load was selected as 1500 pounds, and a Weibull distribution was fit to the transformed data. A comparison of these data at both the

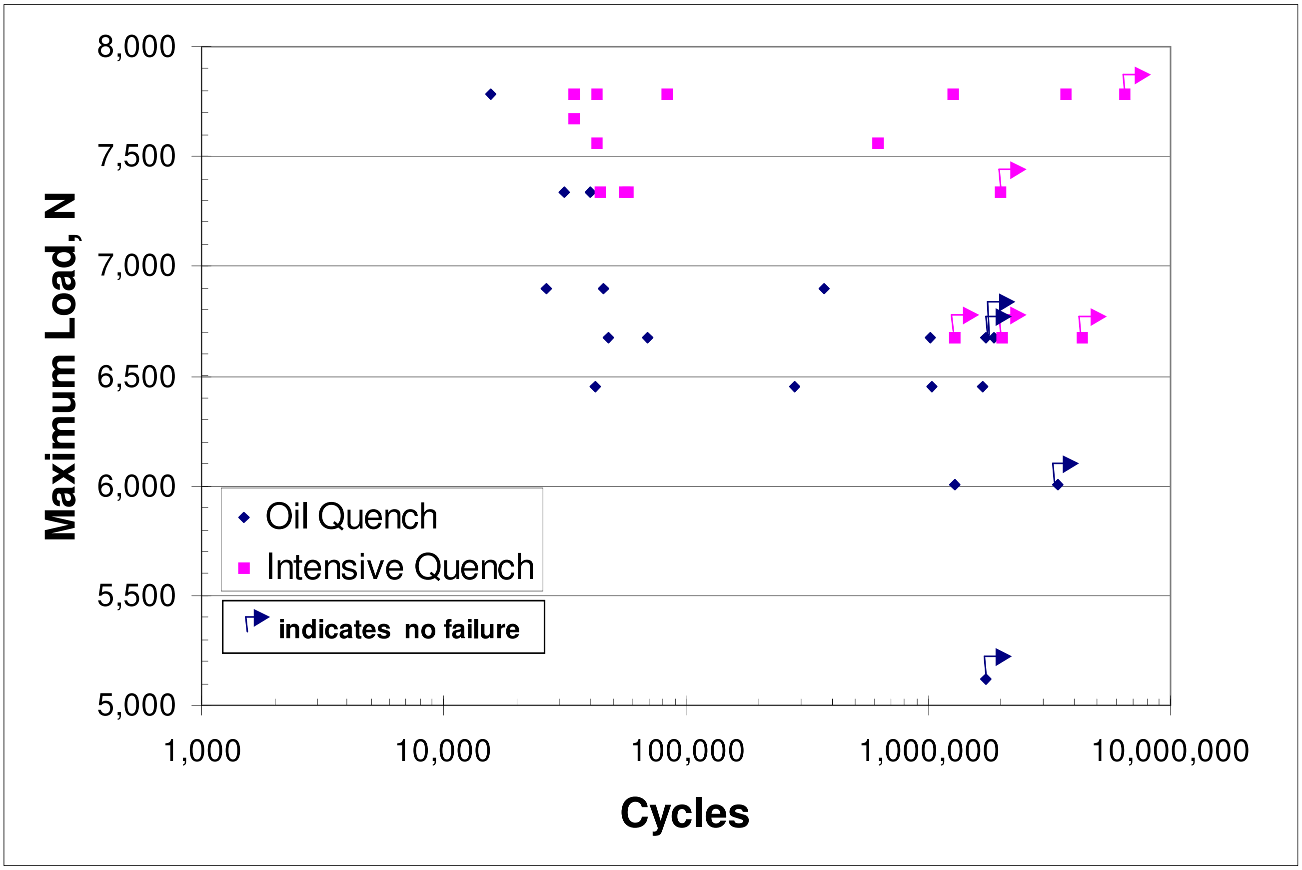

Figure 11. 3-Point Bending Fatigue Data for Carburized and Hardened Pyrowear 53 Notched Test Bars.

10% and 50% lives showed a statistically significant difference between the intensively and quenched and oil quenched test bars, see Table IV. The analysis demonstrates the benefit of deeper residual compressive stress produced by intensive quenching on bending fatigue resistance. At the 50% lives level, the ratio of improvement was 4.2, with 98% confidence level. However, at the tighter 10% life level, the ratio dropped to 1.2, with 60% statistical confidence. The relatively low Weibull shape parameter for both quenched conditions is indicative of scatter in the test data. The difference in the significance of the life data comparison is also indicative of the test data scatter, one probable source being the surface finish of the notch and the fact that grinding was not performed after the milling operation to shape the notch.

Table IV.
Statistical Analysis of Transformed Fatigue Data [13]

	Intensively Quenched Test Bar	Oil Quenched Test Bar
Weibull Shape Parameter	0.458	0.665
10% Life (10^3 Cycles)	25	21
50% Life (10^6 Cycles)	1.5	0.36
Ratio of 10% Lives (IQ/OQ)	1.2	
Statistical Significance	<60%	
Ratio of 50% Lives (IQ/OQ)	4.2	
Statistical Significance	>98%	

Conclusions

This study proved the feasibility of improving bending fatigue strength by altering the hardening process. The intensive quenching process produced a deeper compressive stress state after heat treatment than conventional oil quenching, and this resulted in improved bending fatigue strength.

In addition to the actual test data, this study showed the benefit of using accurate numerical simulation of the carburization and hardening processes to assess the nature of the differences between the processes and to predetermine the quenching conditions required to achieve the goal of deeper residual compression and thus improved resistance to fatigue.

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