It is well established that carburization of low alloy steels promotes compressive residual surface stress upon quenching, and that compressive surface stresses enhance fatigue life. Building upon these principles, a U.S. Army sponsored project is in progress to improve helicopter gear fatigue life through innovative quenching and the achievement of deeper compressive surface stress. The Army has established a goal to improve the power density and life of helicopter transmissions. Using Pyrowear® 53 alloy steel, notched test bars and full test gears have been heat treated by carburizing, quenching, deep freezing, and tempering. The quench methods examined were conventional oil quenching and intensive quenching. Bending fatigue results for these pieces will be discussed in conjunction with heat treatment finite element simulation and X-ray analysis of combined heat treatment residual and gear loading stresses.

**Background**

The steel alloy Pyrowear® 53 is being increasingly used in helicopter transmission gear applications for the U.S. 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 1.

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

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Cu</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.10</td>
<td>0.35</td>
<td>1.00</td>
<td>1.00</td>
<td>2.00</td>
<td>3.25</td>
<td>2.00</td>
<td>0.10</td>
</tr>
</tbody>
</table>
An ongoing project sponsored by the U.S. Army and headed by Deformation Control Technology, Inc., is providing important insights into an innovative quenching process.

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 [1-3]. Developed by 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 compression. As the hot austenitic core cools and thermally contracts, the level of surface compression is deepened significantly. 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 component remains much higher than that of a conventionally quenched component [4-7].

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

ACKNOWLEDGEMENTS:
The authors wish to acknowledge the support of B. Smith and E. Ames of the U.S. Army AATD for their support of this work though the SBIR project #W911W605C0017. Appreciation is also expressed to B. Hansen of Sikorsky Aircraft Corp.; S. Rao of the Gear Research Institute; T. Krantz of the Army Research Laboratory at NASA-Glenn; and J. Powell, M. Aronov, and N. Kobasco of IQ Technologies in Akron, Ohio. Program results describing work in progress were presented at the American Helicopter Society (AHS) International Conference in May 2006.
Heat Treating and Test Loading Simulation

As with the notch bar, an analytical approach was taken for the test gear heat treatment assessment with respect to both quench flow and fixturing design. A proprietary fixture and channeled flow system was developed for intensive quench process, and a comparative heat treatment simulation study conducted to compare the predicted residual stress profiles between the intensive and oil quenched gears.

The resulting magnitude and distribution of predicted residual stresses for both quenching processes are shown in the contour plot illustrated in Figure 15. The figure illustrates the residual stress contours through the mid-plane cross section of the gear.

While both quench methods are predicted to produce nearly identical stress in the tooth itself, both magnitude and distribution of the compressive stress in the root are markedly increased by intensive quenching. The quantitative differences are clearly seen in direct comparison of stress profiles at three locations in the tooth/root cross section (Figure 16).

Here again, as in the notch bar specimens, heat treatment simulation provides useful predictive data concerning magni-
tude and distribution of the gear residual stresses. Figures 17-19 show the predicted residual stress profiles between the oil and intensive quenched simulations at the three locations shown in Figure 16. While the tooth section (A) shows consistent residual compression between the two quenches (Figure 17), surface and subsurface compression at the tooth base (B) (Figure 18) and root center (C) (Figure 19) show significant increases in residual compression to a depth of 1.5 mm (0.059”). This depth is slightly below the carburized case depth of ~0.050”.

For the tooth base the predicted increase is from 71 ksi to 102 ksi, and for the center root from 46 ksi to 90 ksi.

Based on the modeling results, physical test gear specimens were subsequently processed through both oil and intensive quenching. Based on the heat transfer, quench flow characteristics, and process sensitivity determined from the DANTE simulation work, an intensive quench fixturing system was designed for the test gear by IQ Technologies of Akron, Ohio. The system was designed to be readily integrated within pre-existing IQ processing equipment, demonstrating ready adaptation of the technology within a typical heat treatment manufacturing cell. An illustration of the system is shown in Figure 20.
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 stress rates and temperatures encountered during a given heat treat process. Linkage with corresponding phase transformation models then provides 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 [8-10].

In defining material behavior, DANTE’s material model incorporates both rate dependent and independent yielding, kinematic and isotropic hardening, and recovery—all as functions of temperature and metallurgical phase. Isothermal, strain rate controlled tension, and compression tests were run to characterize the stress-strain behavior of Pyrowear 53 as a function of temperature and carbon level. From these stress-strain data the mechanical parameters for DANTE’s mechanical model were determined and entered into the steel database.

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 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.

Steel phase transformation kinetics are most commonly presented in the form of isothermal Time-Temperature-Transformation (TTT) or Continuous Cooling Transformation (CCT) diagrams. For the subject Pyrowear steel, Carpenter Technology Corporation was able to provide a simple TTT diagram and critical temperatures. From this figure, several important heat treating characteristics of Pyrowear 53 were evident. The supplied data indicated that the steel is highly resistant to diffusive phase transformation, with the ferrite/pearlite nose occurring at 704° C (1300° F) after quickly cooling from the austenite range and holding for 15 minutes. This helps to explain the high hardenability of this steel. The specified core martensite start temperature is 510° C (950° F), and the associated carburized case martensite start temperature is 130° C (265°F) [1,2]. Consequently, phase transformation kinetics characterization for simulation focused primarily on the austenite-to-martensite transformation. The material kinetics parameters were implemented into the DANTE steel database after mathematical fitting of dilatometric data obtained through testing a series of carburized samples on ORNL’s quenching dilatometer [11].

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.

Objectives and Program Outline

The primary objective of this program 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, the program focused on achieving the higher power density requirement 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 consisting of a combination of process simulation and physical experiments was defined. The principal goal was to establish two independent material populations based solely on differences in heat treatment, with simulation, physical testing, and bending fatigue test results used to characterize improvement, based principally on the effect of enhanced residual surface compressive stresses. The program is outlined as follows:

- Define heat treatments to be examined (isolation of heat treating effects with respect to residual stress)
- Establish testing program for feasibility assessment
- Predictive materials engineering—simulate heat treatments
- Processing and testing of sample coupons
- Evaluate results
- Assess process sensitivity and enhance process control
- Evaluation and testing of refined process
- Implement analysis and physical testing in full gear components

![FIGURE 1: MODIFIED “V-NOTCH” SAMPLE CONFIGURATION](image1)

![FIGURE 2: SCHEMATIC OF TEST SAMPLE SHOWING CARBURIZED SURFACE](image2)
Analysis and Testing Program

Program Phase I—Feasibility Assessment

To demonstrate the potential for improving the bending fatigue strength of Pyrowear 53 steel for helicopter transmission gears by heat treatment, 25 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 then established, as summarized in Table 2.

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 three-point bending fatigue sample was defined; the notch geometry was consistent with notched flexure fatigue specimens used by Bell Helicopter. The modified “V” notch has a 60° included angle with a 1.16 mm radius (0.0455") to simulate a typical gear tooth root geometry. The test specimen configuration is shown in Figure 1.

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 2. 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.

Process Simulation

Prior to physical heat treating, a series of heat treat models were run to characterize the respective processes to be applied to the test pieces. The use of a simulation tool provided 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 the program.

The Pyrowear 53 material was carburized to a carbon level of 0.80%.
The intensive quench is applied axially to the gear using specially controlled, high-velocity water flow. A fixture with the austenized gear is sealed against a vertical coaxial pipe (shown in Figure 20), which contains specially designed baffles to direct the quench across the various gear surfaces and through the teeth.

Precise timing of quench application and shut-off is essential. As discussed in Table 5, for the planned single tooth bend testing a total of 12 test gears were oil quenched, and 12 gears were intensively quenched using the fixturing system described in Figure 20.
After processing, one of each gear type (oil and IQ) was tested in X-ray diffraction to assess both residual stress magnitudes and variability relative to the simulation predictions. Residual stress profiles were taken at two locations for each gear, with the profile made at the center root location (“Position C” in Figure 16). The X-ray testing orientations taken on the gears are shown schematically in Figure 21.

The measured X-ray residual stress profiles from each gear are compared with their corresponding simulation predictions in Figure 22. The predicted residual stress profiles for both oil and intensively quenched gears displayed excellent agreement with the stresses calculated from X-ray measurements. Also, the intensively quenched gear exhibited ~40% increase in residual compression over the baseline oil quench to a depth of 0.050”.

Based on the modeling and X-ray test results—as well as the results of residual stress/three-point bending fatigue evaluation conducted in the early part of this investigation—results of the single tooth bending fatigue testing currently underway are predicted to show strong promise for intensive quenching providing substantial enhancement in bending fatigue performance over the baseline oil quenching process.

An additional engineering utility of the DANTE heat treatment simulations is the ability to analyze composite stresses in the gear. Stresses generated in gear loading are of course affected by the residual stresses generated in the heat treatment. Quantitative assessment of the composite stress is not straightforward, and has typically been done under the assumption that the stress states are additive.

Simulation results illustrating this interaction for both the oil intensively quenched gears are shown in Figures 23-25. The nonlinear response of residual stress at the tooth base is clearly evident in the comparative stress plots presented in Figure 23. The graph compares the pre-loaded tooth base residual stress profile with that under a 900 lb. tooth load. The simulation provides important data concerning the non-linear response, as well as information concerning depth relationships. From a design standpoint, this type of analysis provides an important tool in engineering residual stresses to meet complex loading requirements.

Additional insight into behavior of the composite stresses can be gained through examination of cross-sectional contour maps such as those shown in Figures 24 and 25. For example, in the oil quenched gear (Figure 24) one can see localized tensile regions below the tooth. This region increases in both volume and magnitude when the tooth is subjected to loading. In contrast, the intensively quenched gear (Figure 25) shows a much smaller sub-tooth tensile region, which does not increase significantly during loading. Such characterization is valuable in understanding potential fracture path and failure mode. Therefore extending heat treatment simulation to include subsequent loading represents an important engineering design milestone.

**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... CONTINUED ON PAGE 50
the worst performance with near 50 percent residual stress drop-off at both outer edges. Also, the stacked configuration displayed a wide region in the bar interior with tensile stress on the order of 330 MPa, extending through the bar thickness. The magnitude and spread of these tensile stresses are not as pronounced in configurations A and B. Thus from a residual stress standpoint, expectations were for configuration A to show superior bending fatigue performance as compared with the oil quenched samples (see oil stresses in Figure 5). Configuration B would be expected to show inferior, or at best similar performance to the oil quench. Configuration C samples were not physically evaluated.

**Physical Testing of Simulated Quench Configurations**

In continuing the notch bar fatigue characterization, 84 additional notch bar samples were prepared using a carefully planned design-of-experiments approach to physically quantify the findings revealed in the DANTE simulations. Table 4 details this second notch bar testing plan.

To facilitate the normal and parallel directional flow, a new fixture was developed for the notch bars for use in the quench processing equipment. The fixture was a stainless steel cylinder in which the notch bar was positioned diametrically. During austenitization, the entire fixture assembly (with sample) was heated. Transfer of the fixture into the quenching unit was rapid and highly consistent, with the entire assembly easily placed within the IQ water flow tube. Comparative X-ray and simulation residual stress calculations are presented in Figure 11.

As in the review of the surface stress simulation predictions, examination of the residual stress profiles would also indicate superior bending fatigue performance of the IQ-face samples (config. A) over the oil quenched and parallel quenched specimens (config. B). Bending fatigue test data for this evaluation is shown in Figure 12. The new data showed a marked reduction in scatter, as both overall notch surface quality was improved and process stability was enhanced. Most importantly, the bending fatigue test data parallels exactly the expected per-

---

**Table 4: Test Matrix for Phase IA**

<table>
<thead>
<tr>
<th>Process Configuration</th>
<th>No. Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil Immersion Quench</td>
<td>20</td>
</tr>
<tr>
<td>IQ – Quench Normal to Notch Face (A)</td>
<td>20</td>
</tr>
<tr>
<td>IQ – Quench Parallel to Notch Face (B)</td>
<td>20</td>
</tr>
</tbody>
</table>

---

**FIGURE 12:**

*Notch Bar Bending Fatigue Performance*  
Ground Notch with Tighter Process Control

**FIGURE 13:**

*Gear Specifications*

- No. Teeth: 40
- Dia. Pitch: 10
- Pressure Angle: 20°
- Pitch Dia.: 4.00
- Base Cir. Dia.: 3.75
- Outside Dia.: 4.25
- Tooth Thickness: 0.11

**FIGURE 14:**

*Test Gear for Single Tooth Bending Fatigue Evaluation*

**FIGURE 15:**

*Residual Stress Profile Comparison after Heat Treat Through Tooth/Root Cross Section*

**FIGURE 16:**

*Reference Directions Points in Tooth/Root Cross Section*
formance as predicted in the simulations.

The IQ-faced quenched samples showed a clear maximum cyclic load limit of 1,825 lbs., whereas the samples quenched in the standard oil quench practice showed a clear limit at 1,650 lbs. Also consistent with the simulation stress predictions and X-ray calculations were the IQ-parallel quench samples, which performed slightly worse than the oil quenched material.

**PROGRAM PHASE II—IMPLEMENTATION INTO FULL GEAR COMPONENT**

With the strong feasibility demonstrated in Phase I and Phase IA for achieving the bending fatigue life increase goal, the next phase was initiated to extend the evaluation to full gear components. Through consultation with both the U.S. Army AATD and military helicopter OEMs, a simple spur gear design was selected as the test component for the second phase of this project. Configuration and summary gear specifications are shown in Figure 13.

Prior to quench hardening, the gears were vacuum carburized selectively on the teeth surfaces, with copper plating masking the balance of the gear as shown in the related figure.

**Process and Testing Plan**

The effect of intensive quenching on the bending fatigue strength of the Pyrowear 53 gear is currently being evaluated by single tooth bend testing. The configuration of the test apparatus is shown schematically in Figure 14. In the test, a cyclic load is applied to two teeth via a movable upper anvil and a stationary lower anvil, with the gear remaining fixed by a shaft support. For this tooth bending test, the evaluation plan shown in Table 5 was developed to quantitatively assess single tooth bending fatigue improvement.

**FIGURE 17: RESIDUAL STRESS PROFILE COMPARISON (RADIAL STRESS) AT POSITION (A) IN TEST GEAR; FROM SIMULATION**

**FIGURE 18: RESIDUAL STRESS PROFILE COMPARISON (HOOP STRESS) AT POSITION (B) IN TEST GEAR; FROM SIMULATION**

**FIGURE 19: RESIDUAL STRESS PROFILE COMPARISON (HOOP STRESS) AT POSITION (C) IN TEST GEAR; FROM SIMULATION**

*B&R Machine and Gear Corporation*

**CUSTOM BEVEL GEAR MANUFACTURING**

*PER YOUR SPECIFICATIONS AND/OR SAMPLE PROVIDING INVERSE ENGINEERING TO MAKE A CLONE OF YOUR SAMPLE*

- SPIRAL BEVEL GEARS: 66" PD
- STRAIGHT BEVEL GEARS: 80" PD
- SPURS-HELICALS-SPLINE SHAFTS
- GEARBOX REPAIR/REBUILDS

**BREAKDOWN SERVICES**

4809 U.S. HIGHWAY 45 • SHARON, TN 38255
TOLL FREE: (800)-238-0651 • PHONE: (731)-456-2636 • FAX: (731)-456-3073
EMAIL: inquiry@brgear.com • www.brgear.com

Family owned and operated since 1974
seemingly insignificant, produced a distinct variation in the surface residual stress profile across the notch surface.

Simulations showed that the surface residual stress below the notch could vary from –600 MPa (87 ksi) at the outer edge to –45 MPa (6.52 ksi) at the center. This critical finding illustrates both the utility and importance of a simulation design tool in understanding and optimizing a manufacturing process such as heat treatment. With this information, modifications to the IQ valve system were made accordingly.

Future plans also include computer control with data recording of operation and water application.

Coupling improved flow control with enhanced notch surface quality achieved by grinding, the next variable examined was the orientation of the part relative to the quench flow. Here again, process simulation with the DANTE design software demonstrated critical value. With the goal being optimal application of intensive quenching, three new configurations were examined (each configuration is illustrated schematically in Figure 8).

DANTE simulations were conducted for each of these configurations to determine sensitivity of stress magnitude and distribution as a function of intensive quench flow orientation. As in the flow timing diagnostic work previously discussed, profiles of the resulting residual stresses across the surface notch were compared for each case. The plot in Figure 9 displays the results, while Figure 10 shows contour maps of the final residual stress through the notch cross section for each case. What appears immediately evident from the simulations is that, as seen with flow timing application, the orientation of the part relative to flow also has a significant effect on residual stress—specifically the stress distribution.

Configuration A (normal flow) displayed the most consistent and uniform residual stress, with minimal variation in stress magnitude across the length of the notch. With flow parallel to the notch in processing a single sample (configuration B), stress magnitude remains relatively uniform from the leading edge through the center, but drops off rapidly at the trailing edge by nearly 50 percent (225 MPa vs. max. compression of ~450 MPa). The stacked configuration (C), with both outer edges essentially insulated, showed...
COMPARISON OF PREDICTED SURFACE RESIDUAL STRESS ACROSS THE ROOT OF THE SAMPLE NOTCH.

PREDICTED CROSS SECTION RESIDUAL STRESS CONTOURS FOR 3 QUENCH CONFIGURATIONS

TECH INDUCTION
ENGINEERED INDUCTION TOOLING

22819 Morelli Drive., Clinton Twp., MI 48036
586-469-TECH (8324)
Fax: 586-469-4620

TECH INDUCTION
ENGINEERED INDUCTION TOOLING
- Consultation
- Custom Design Work
- Repair
- Prototype
- Transformers
- Increase Coil Life
- Control Heat Pattern
- Enhance Flux Field
- Updated CAD/CAM/CAD Key
- Complete Design/Engineering Facilities

SAET
TECHNOLOGY and EQUIPMENT for INDUCTION HEATING
- Automatic or Manual Machines for Heat Treating
- Automatic or Manual Machines forForging
- Medium Frequency Induction Melting
- Brazing Equipment
- Feeders — Handling — Robotic Equipment
- Cooling Systems
- Matching Transformers — High/Med/Low Frequencies

FORGE TOOLING
- Forge Coils
- Oval Coils
- Channel Coils
- Pigeon Hole Coils
- Melting Coils
- Capacitors
- Transformers
- Skid Rails
- Water Manifolds

www.techinduction.com

gearsolutionsonline.com • JULY 2006 • GEAR SOLUTIONS
percent 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 OEMs. The 3-D mesh for the simulation is shown in Figure 3.

Simulations were also performed to assess the probable effects on residual stress and hardness between oil and intensive quenching processes. Table 3 summarizes the process steps for each of the evaluated quenching operations after carburization. Simulation of the quenching was performed through application of heat transfer coefficients for the oil or intensive quenching, and the subsequent cryogenic treatment. The DANTE tempering model was employed for the temper operation. The simulations indicated a marked enhancement in both surface and subsurface residual compression for intensive quenching. Therefore, physical processing and testing was initiated on the Pyrowear bend test coupons. Predictions of hardness and residual stress are compared against measured values in the next section.

Physical Characterization

Upon completion of the heat 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 4; 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 0.02" (0.5mm).

Both a conventional oil quenched 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. Measurements were taken at 0.2 mm (0.008") increments, to a depth of 1.2 mm (0.047"). The simulation and the measured test results display excellent agreement, as shown in the plot presented in Figure 5. The project methodology proved the value of process simulation as a predictive design tool.

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 quickly after crack development, strain gages were applied to the samples at the notch root.

Eighteen oil quenched and 17 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 6 shows the 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, Figure 6 shows 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 that 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 carburized 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 1,500 pounds, and a Weibull distribution was fit to the transformed data. A comparison of these data at both the 10- and 50-percent lives showed a statistical difference between the intensively and quenched and oil quenched test bars (see Table 3) [13]. The analysis demonstrates the benefit of deeper residual compressive stress.
produced by intensive quenching on bending fatigue resistance. At the 50-percent life level, the ratio of improvement was 4.2, with a 98-percent confidence level. However, at the lower 10-percent life level, the ratio dropped to 1.2, with just a 60-percent 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 of scatter was the surface finish of the notch and the fact that grinding was not performed after the milling operation to shape the notch.

PHASE IA—PROCESS SENSITIVITY AND REFINEMENT
Simulation in Process Sensitivity Assessment

The data scatter seen in the initial notch bar testing necessitated additional investigation into IQ process variables and sensitivity. The DANTE predictive heat treatment software tool provided significant insight into the process sensitivity, particularly with respect to the effect of variation in water flow and application time.

The initial quench configuration used for the notch bar samples was a fixture system in which the water flow was directed parallel to the longitudinal direction of the sample, as shown schematically in Figure 7.

Using the DANTE software, DCT executed a series of heat treatment simulations to characterize the sensitivity of resulting residual compressive stress in the sample with respect to water flow application and timing. It was found that full flow must be achieved within \( \leq 1.0 \) seconds from initial quench application to develop the temperature gradient required to achieve the deep compressive residual stresses. This information is crucial because it demonstrates quantitative sensitivity data for quenching this type of root geometry. The shift in thermal gradient caused by an initial reduced flow, although

3-POINT BENDING FATIGUE DATA FOR CARBURIZED AND HARDENED PYROWEAR 53 NOTCHED TEST BARS.

PHASE I QUENCH CONFIGURATION
heat treatment than conventional oil quenching, and this resulted in improved bending fatigue strength.

In addition to 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, thus improved resistance to fatigue. Finally, the utility and importance of considering composite (heat treatment residual and loading) stresses in assessing gear loading was also shown. Further work in this area by DCT includes expansion of the simulation capabilities to include both mechanical shot and laser shock peening effects in further enhancing composite residual stresses in a carburized gear. Preliminary work in this area is also underway within a related U.S. Army sponsored project.

REFERENCES


ABOUT THE AUTHORS:

A.M. Freborg, B.L. Ferguson, and Z. Li are with Deformation Control Technology, Inc., which is based in Cleveland, Ohio. Go online to [www.deformationcontrol.com]. D.X. Schwam is with Case Western Reserve University, and B.J. Smith is with the U.S. Army AATD, which is located in Fort Eustis, Virginia.