2002-01-1003

Optimized Carburized Steel Fatigue Performance as Assessed with Gear and Modified Brugger Fatigue Tests

Jason J. Spice and David K. Matlock
Colorado School of Mines

Greg Fett
The Dana Corporation

ABSTRACT

The effectiveness of three different techniques, designed to improve the bending fatigue life in comparison to conventionally processed gas-carburized 8620 steel, were evaluated with modified Brugger bending fatigue specimens and actual ring and pinion gears. The bending fatigue samples were machined from forged gear blanks from the same lot of material used for the pinion gear tests, and all processing of laboratory samples and gears was done together. Fatigue data were obtained on standard as-carburized parts and after three special processing histories: shot-peening to increase surface residual stresses; double heat treating to refined austenite grain size; and vacuum carburizing to minimize intergranular oxidation. Standard room-temperature S-N curves and endurance limits were obtained with the laboratory samples. The pinions were run as part of a complete gear set on a laboratory dynamometer and data were obtained at two imposed torque levels. The number of cycles to failure was used to evaluate the effects of processing history.

Based on laboratory endurance limits, shown in parentheses, the processing histories ranked as follows: shot-peened (1410 MPa), vacuum carburized (1210 MPa), reheated to refine grain size (1140 MPa), and as-gas-carburized (1000MPa). In the gear set tests, shot peening also proved to be the most effective way to improve fatigue life at both imposed torque levels. The results of this study show that data on laboratory samples can be used to interpret the fatigue performance of gears.

INTRODUCTION

The bending fatigue and fracture properties of carburized steels have been evaluated with laboratory cantilever bend specimens (1-5), single-tooth bending fatigue tests (4,6-8), full-scale gear tests in operating systems and other alternate testing geometries (9). To obtain systematic analyses of alloying and processing variables, laboratory bend samples have been used and several geometries have been considered (1,10). Of particular interest here are the results from recent studies based on single specimen geometry and reviewed by Wise *et al.* (2,3). The laboratory specimen incorporated a filet radius designed to simulate the root of a gear tooth and variables of interest included base alloys and impurity contents, carburizing parameters including gas composition and carburizing process, and shot peening. In addition to fatigue-life data and endurance limits, data were obtained on retained austenite contents, prior austenite grain sizes (in the case), residual stress profiles, hardness profiles, surface finish, and oxide depths along prior austenite grain boundaries. It has been determined that the three most effective ways to improve bending fatigue endurance limits are to increase the residual compressive stresses at the surface, refine the case prior austenite grain size, and minimize intergranular oxidation at prior austenite grain boundaries (2,3).

While development of fatigue data on laboratory cantilever beam bend samples provides a cost-effective method to assess systematic variations in process variables, microstructural and geometry characteristics important for fatigue performance may differ from carburized production gears. For example, due to the small size and corresponding higher cooling rates experienced on quenching, core hardness levels in laboratory samples are typically higher than observed in gears (4). The corresponding differences in hardness and microstructural gradients may correlate to differences in residual stress and retained austenite profiles, both important to fatigue performance. Also laboratory specimens are chemically polished prior to carburizing and thus may exhibit a lower surface roughness in comparison to production gears in which root radii are typically carburized with an as-machined surface finish.

Conclusions based on the fatigue behavior of laboratory samples have been successfully used to guide modifications in alloy selection and process histories for production gears. However, limited systematic comparisons have been made to directly compare fatigue results from laboratory samples and commercial gears. Thus, the purpose of this paper is to present the results of one such comparison study. Fatigue data on commercial pinion gears, produced from forged SAE 8620 blanks and tested on a dynamometer, are compared to results on laboratory samples, which utilized the modified Brugger sample considered in previous studies (1-5). Four sample sets, each which included both production gears and laboratory samples, were chosen to reflect the significant variations in the fatigue behavior observed in laboratory samples (2,3). The processing histories included an as-gas-carburized set as a baseline, a set shot-peened after gas carburizing, a reheated set to refine the case grain size, and a set processed by vacuum carburizing to minimize intergranular oxidation at the surface.

EXPERIMENTAL PROCEDURE

MATERIAL AND SPECIMEN PREPARATION – SAE 8620 steel, with the composition shown in Table 1, was commercially produced into pinion gear forgings. The pinion forgings were upset from 38.1 mm (1.5”) diameter bar stock. Then, the forgings were machined to the final pinion dimensions. Modified Brugger samples were machined from the stems of some of the pinions. A schematic drawing of the location of the modified Brugger samples is shown in Figure 1 and the sample geometry is shown in Figure 2.

Table 1. Chemical Composition (in wt. %) of SAE 8620 Steel.

C	**Mn**	**P**	**S**	**Si**
0.22	0.86	0.013	0.013	0.24
Cr	**Ni**	**Mo**	**Cu**	**Al**
0.54	0.46	0.18	0.11	0.019
O	**N**	**V**	**Nb**	
00.7	0.010	0.004	0.003	

The remaining pinion blanks were commercially processed into pinion gears and matched with a set of ring gears for testing on a dynamometer. In this study, only the pinions were analyzed and the ring gears were used to facilitate dynamometer testing.

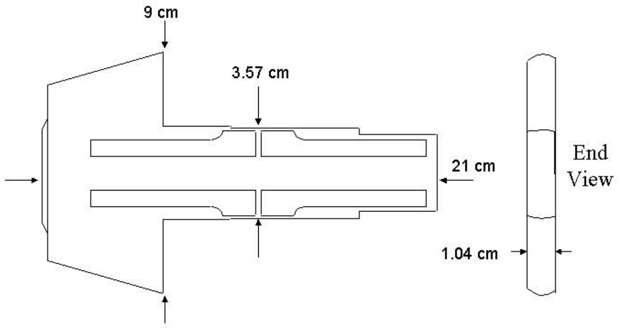

Figure 1. Schematic drawing of the location of the modified Brugger samples machined from pinion blanks.

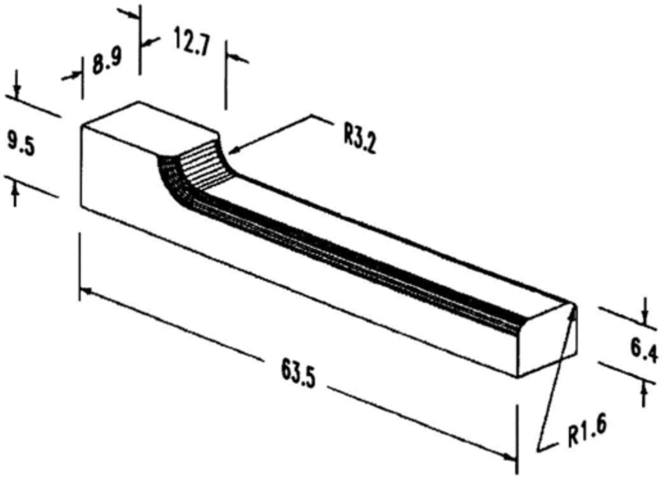

Figure 2. Schematic drawing of the modified Brugger fatigue specimens. Dimensions are in millimeters.

Table 2. Summary of Processing Steps for the 4 Conditions

Condition	**Process History**
Baseline	Gas carburized, quenched and tempered
Shot-Peened	Gas carburized, quenched, tempered and shot-peened.
Reheated	Gas carburized, quenched, tempered, reheated and quenched.
Vacuum Carburized	Vacuum carburized, quenched and tempered.

CARBURIZING/PROCESSING - Four processing histories, designated baseline, shot-peened, reheated, and vacuum carburized and summarized in Table 2, were used in this study. Each processing history was simultaneously applied to groups of modified Brugger samples and commercial gears. The baseline, shot-peened and reheated conditions were gas-carburized at 893°C (1640°F) for 380 minutes with a carbon potential of 1.27 at the beginning and 1.14 during the soak. The parts were then quenched in oil at 121°C (250°F), and tempered at 149°C (300°F) for 1 hour. The vacuum carburized samples were carburized with a processing history designed to produce carburizing conditions which match those obtained by the gas-carburizing process. The vacuum carburized samples were heated to 900°C (1652°F) over a 90 minute period. The carburizing time was 26 minutes with a diffusion time of 162 minutes. The parts were then cooled to 870°C (1600°F) over a 10 minute period. The parts were held at this temperature for 25 minutes. The total cycle time was 313 minutes. The parts were then quenched in 80°C (176°F) oil for 15 minutes and tempered at 150°C (300°F) for 2 hours.

After carburizing, the shot-peened condition was shot-peened with MI-330-H shot with 150% coverage. The intensity of the shot peening was measured using a type C Almen strip with an arc height between 0.19 and 0.23 mm (0.0075 and 0.009 inches).

After processing with the as-carburized condition, one group of modified Brugger samples and pinions was reheated to 838°C (1540°F) for 20 minutes in a neutral atmosphere and then quenched in 82°C (180°F) oil. This history was designed to refine the prior austenite grain size. The samples were not re-tempered after the reheat and quench. This is not believed to affect the fatigue performance.

Prior to carburizing, the modified Brugger specimens were chemically polished in a $HF-H_2O_2-H_2O$ solution following procedures used previously (5). Following conventional industrial practice, the pinions were carburized in the as-manufactured condition, i.e. without chemical processing.

TESTING - The modified Brugger fatigue specimens were tested in cantilever bending fatigue with a displacement controlled fatigue machine operating at 30 Hz. The minimum/maximum stress ratio applied during testing was 0.1 and a value of 10 million cycles without failure was used as the endurance criterion. Three specimens were tested at a given stress level. The stress was lowered in 69 MPa (10 ksi) increments until three successive run-outs occurred. The stress was then increased by 34 MPa (5 ksi) to determine a final endurance limit.

The pinions were tested on a commercially available dynamometer operating at 625 RPM (10.4Hz) at the pinion. Due to the time and cost of testing pinions on the dynamometer, only 5–7 pinions were tested at each of two torque levels. Both torque levels were chosen to be in the finite life region of the S-N curve so that information could be collected on the fracture characteristics.

RESIDUAL STRESS/RETAINED AUSTENITE – Residual stress profiles were obtained from the filleted region of the modified Brugger specimens. Measurements were made using a Microstress Analyzer via X-Ray diffraction. Plots were developed of 2θ vs. Sin(F) for several (F) angles. The retained austenite was determined by the ratio of the austenite and martensite curves.

The depth was altered by electropolishing using a saturated salt water solution. The depth was determined using dial micrometers. No measurements were taken from the pinions.

PRIOR AUSTENITE GRAIN SIZE - One sample from each specimen type and condition was etched to determine the core prior austenite grain size. This was done using 100 mL of picric acid mixed with 2 mL of Tepol soap and 2 drops of HCl. The samples were submersed for approximately 1 minute and then wiped clean with a cotton ball lightly back-polished on a 0.25 micron diamond polishing wheel. The back polishing step was done to remove the appearance of the martensitic structure to enhance the prior austenite grain boundary features.

The prior austenite grain size was measured by counting the number of intersections between grain boundaries and three circles totaling 500 mm in length. Five different regions were counted and averaged. The number of intersections per 500 mm was used to determine the ASTM grain size and mean intercept values.

INTERGRANULAR OXIDATION - One sample from each specimen type and condition was polished at the surface and the intergranular oxidation that occurs during carburizing was observed at 1000 X in a light microscope. The observations were made near the fillet in the modified Brugger samples and at the root for pinions. These samples were not etched.

CASE DEPTH - Two methods were used to determine the case depths. The first method utilized was microhardness (1 kg for 10 seconds) traverses starting at the surface, and case depth was defined as the depth to 50 HRC. Hardness testing on the modified Brugger specimens was performed near the fillet radius of the sample and the pinions were tested at the root perpendicular to the surface. Because the laboratory samples are significantly smaller than the pinions, they are quenched more aggressively. This more aggressive quenching would lead to higher amounts of martensite throughout the sample, thus increasing the hardness in the core of the laboratory samples. This causes the laboratory samples to appear to have a deeper case depth. As an alternative method, case depths were measured visually on samples “over-etched” in 5% nital solution. The case depth was then measured using an image-analyzing device by identifying a change of 50% from the case microstructure to the core.

RESULTS

LABORATORY FATIGUE DATA - Maximum bending stress versus number of cycles to failure (S-N) data are shown in Figures 3. In each figure, open symbols indicate samples that failed and closed symbols indicate run-out (i.e. no failure). For the Brugger samples, run-out was defined as 10 million cycles. In each figure, data are interpreted with two lines. The line through the high stress data represents a best-fit line based on the B_{50} life calculated by a Weibull analysis. The stress level where three consecutive specimens exhibited run-out is defined as the endurance limit and is indicated in the figures by a horizontal line. The endurance limits are summarized in Table 3 and indicate that the shot-peened, reheated, and vacuum carburized conditions all exhibited endurance limits significantly greater than the as-carburized base material. The highest value, 1,400 MPa, was observed for the shot-peened samples.

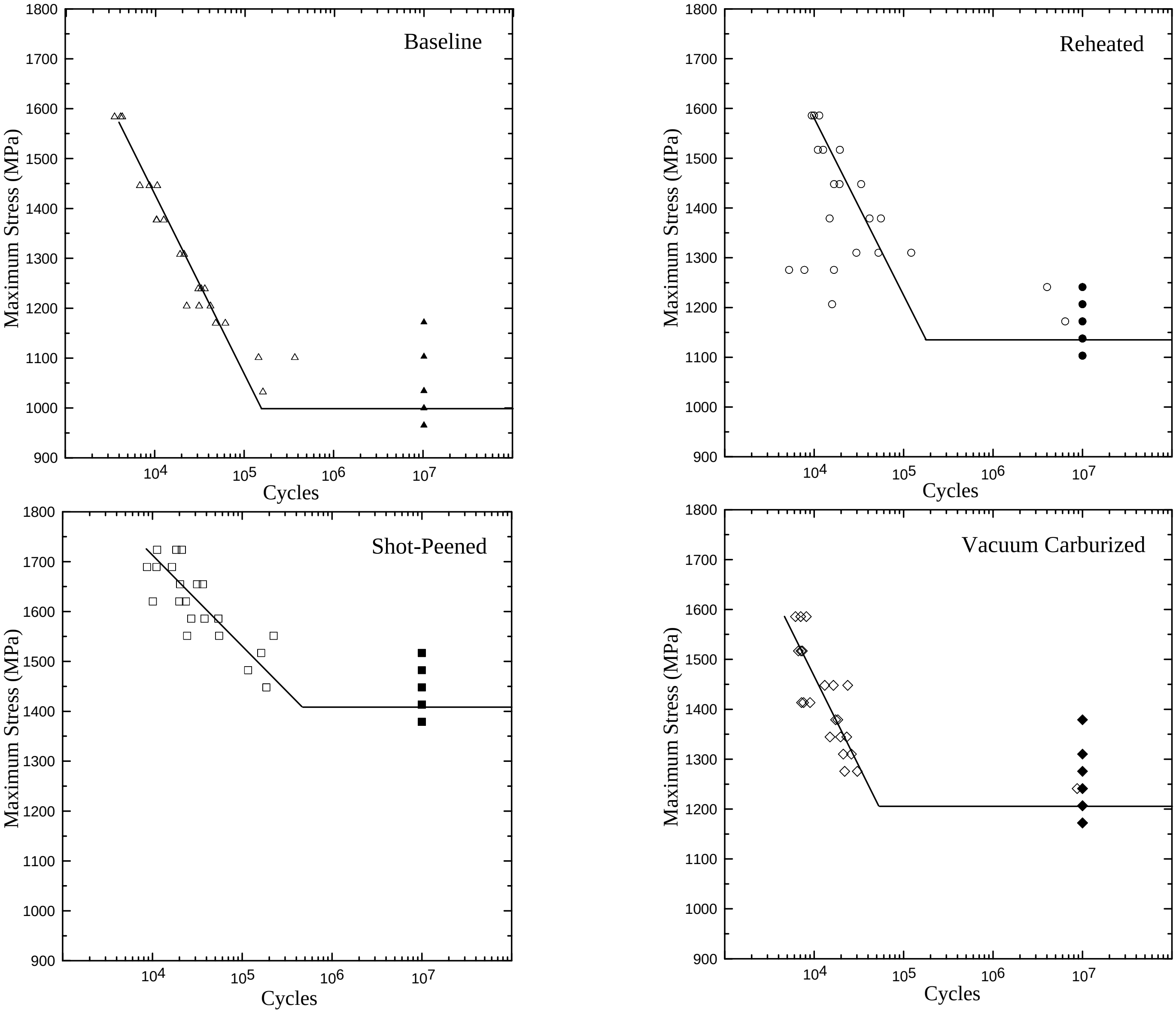

Figure 3. S-N data for the four different conditions of 8620 steel

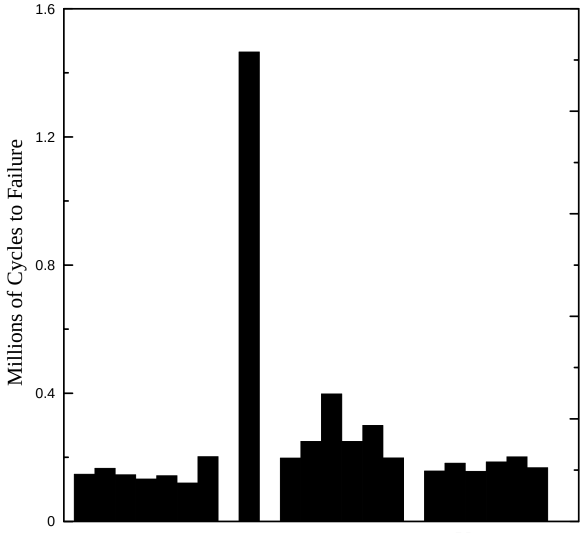

Figure 4. Graph indicating the number of cycles to failure for each pinion in each condition at the "Low" torque level.

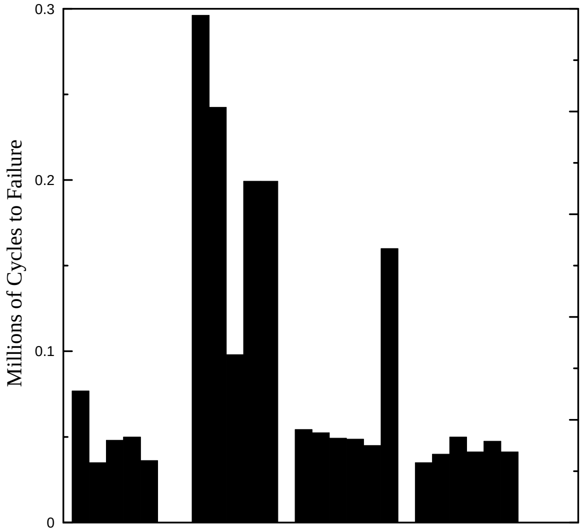

Figure 5. A bar graph indicating the number of cycles to failure for each pinion in each condition at the "High" torque level.

Table 3. Endurance limits for the four conditions of the modified Brugger specimens. The values are reported in MPa.

	Endurance Limit (MPa)
Baseline	**1,000**
Shot-peened	**1,410**
Reheated	**1,140**
Vacuum Carburized	**1,210**

PINION FATIGUE DATA – Fatigue data for the pinions are summarized in Figures 4 and 5. Five to seven pinions were tested at each of two output torque levels: 4,920 and 2,910 Nm (43,500 and 34,900 in-lbs) and the results summarized in Figures 4 and 5 are for samples that failed by root bending fatigue. Some pinions failed by torsional fatigue in the stem at the pinion head and others were suspended without failure due to equipment time limitations 2 million cycles. The test condition most affected by the alternate failure mode was the shot-peened sample tested at the low torque where Figure 4 indicates that only one sample failed by root bending fatigue. For the other samples, one failed by stem torsion fatigue at 2,009,000 cycles, one failed by premature differential case trunnion failure at $1.1X10^{6}$ cycles, and two samples were suspended.

For these four samples the measured lives represent the minimum life for root bending fatigue and illustrate that the root bending fatigue would have exhibited longer life.

The variability in fatigue life is evident by comparing the bars within a given sample group. The B_{50} lives for all pinion test conditions are summarized in Table 4. An estimated lower limit for the low-torque shot-peened tests (shown by the data in parentheses) is also included based on a consideration of test conditions and failure modes.

Table 4. B_{50} life of the pinions for each condition and torque level.

B50	**Baseline**	**Shot-Peened**	**Reheated**	**Vac. Carb.**
Low Torque	152,000	(1,466,000)	266,000	176,000
High Torque	49,000	220,000	63,000	43,000

RESIDUAL STRESS/RETAINED AUSTENITE – The residual stress profiles are shown in Figure 6. The residual stress for the baseline, reheated and vacuum carburized conditions are fairly constant ranging between –100 and –300 MPa. For the shot-peened condition, the magnitude of the compressive stress is significantly greater starting at -715 MPa at the surface and maximizing at –1180 MPa at a depth of 0.075 mm.

Retained austenite measurements were also obtained on the modified Brugger samples and the results are shown in Figure 7. The retained austenite content is approximately the same (13–18%) for all conditions away from the surface and is lower at the surface. The shot-peened condition has significantly reduced amounts (less than 5%) at the surface because some of the retained austenite is mechanically transformed to martensite.

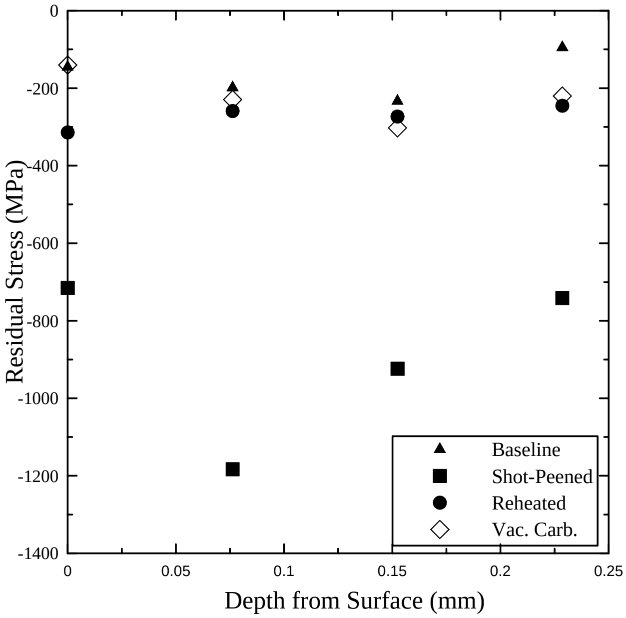

Figure 6. Residual stress profile of the modified Brugger specimens for each condition.

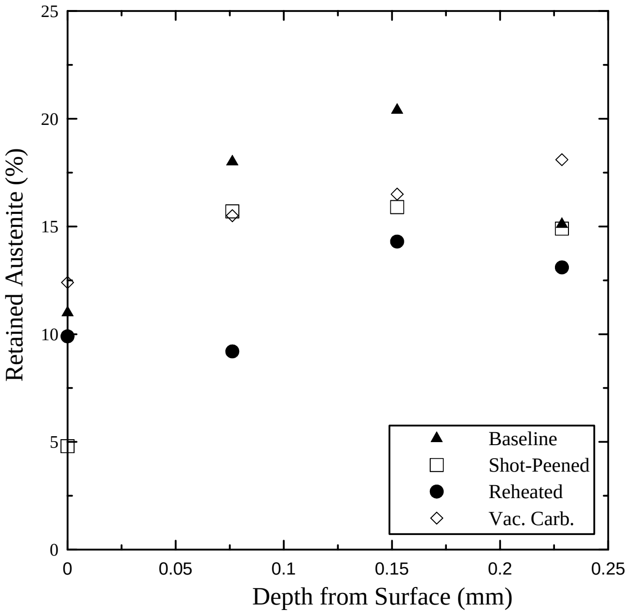

Figure 7. Retained austenite profile of the modified Brugger specimens for each condition.

GRAIN SIZE – A representative micrograph of the prior austenite core grain structure is shown in Figure 8. A summary of the ASTM grain size and mean intercept length is presented in Table 5.

The grain sizes for the baseline and shot-peened conditions are essentially the same for both specimen types. The reheated samples did show a small amount of grain refinement (8.5 μm vs. 12 μm for the Brugger baseline samples). The vacuum carburized condition produced grain sizes that were approximately the same as the baseline condition.

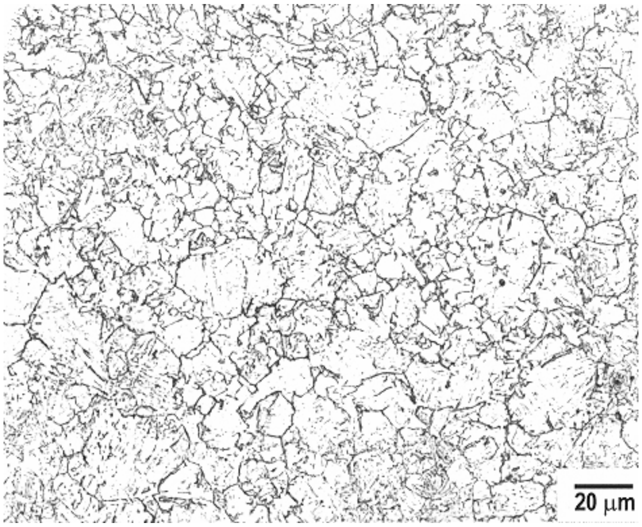

Figure 8. Representative micrograph of prior austenite grain size of SAE 8620 steel etched with picric acid and Tepol for the baseline pinion.

Table 5. Summary of the ASTM grain size and mean intercept length in microns for both specimen type and condition. The ASTM Grain Size is +/- 0.25 and the mean intercept is +/- 0.5 microns.

	Brugger		**Pinion**	
Condition	ASTM (No.)	Mean Intercept (µm)	ASTM (No.)	Mean Intercept (µm)
Baseline	9.5	12	9.25	13
Shot-Peened	9.5	12	9.25	13
Reheated	10.5	8.5	10	10
Vac. Carb.	9.75	11	9	14

INTERGRANULAR OXIDATION – A representative micrograph of the intergranular oxidation at the pinion root is shown in Figure 9. The oxidation depths, measured in microns, are summarized in Table 6. The measurements were taken at the root of each specimen type.

The oxidation depths along grain boundaries are the same for both specimen types and are all essentially equivalent (i.e. 16 - 18 µm). The vacuum carburized samples exhibited no measurable oxidation, as was expected.

CASE DEPTH – Case depth measurements from hardness profiles and visual analysis of etched samples are shown in Table 7. The case depth for the pinions is consistently smaller than the modified Brugger specimens. The difference in case depth reflects that the quench rate in the smaller modified Brugger samples is significantly greater than that achieved in the large pinions. As a result, the core hardness is also greater in the laboratory samples (45 HRC vs. 30 HRC for the pinions).

Both the hardness profiles and visual analysis provide equivalent observations with respect to the effects of process on case depth. The case depth is the same for the baseline, shot-peened and reheated conditions, but is lower for the vacuum carburized condition. However, for each condition, the measured case depths are slightly less based on visual analysis (1.2 mm effective case depth vs. 1.0 mm for visual analysis)

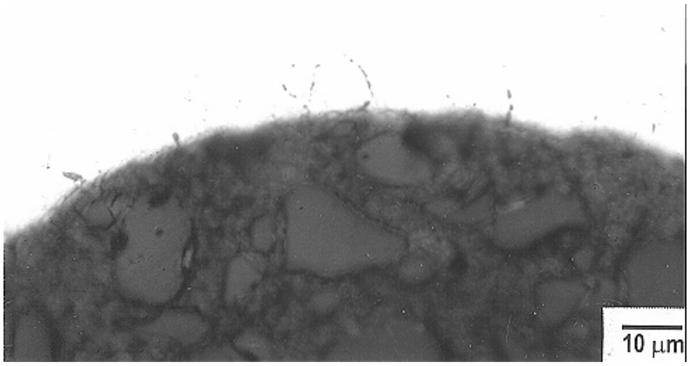

Figure 9. As-polished micrograph taken at 1000X of intergranular oxidation at the pinion root of the baseline material.

Table 6. Summary of the oxidation depth along grain boundaries of both specimen types and condition. Measurements are in microns.

Condition	**Baseline**	**Shot-Peened**	**Reheated**	**Vac. Carb.**
Brugger	17	16	16	0
Pinion	18	17	16	0

Table 7. Summary of the case depth as determined with microhardness testing and visual inspection. Dimensions are in millimeters.

Brugger	**Baseline**	**Shot-Peened**	**Reheated**	**Vac. Carb.**
Hardness	1.2	1.1	1.2	0.8
Visual	1.0	1.0	1.0	0.7
Pinion Root	**Baseline**	**Shot-Peened**	**Reheated**	**Vac. Carb.**
Hardness	0.7	0.7	0.8	0.6
Visual	0.9	0.8	0.9	0.6

DISCUSSION

To directly compare, on a single stress-life plot, the fatigue data from the modified Brugger specimens tested in the laboratory with data obtained on the pinions, the actual imposed bending stress at the pinion root must be known. The imposed test conditions on the pinions tested in the dynamometers was torque. To provide a method to compare the two data sets the following graphical method, based on the modified Brugger fatigue data, was employed. The result provides a semi-quantitative comparison of the relative effects of the different processing conditions on the two data sets.

To determine an effective imposed root bending stress on the pinions, the average fatigue lives of the baseline pinion samples tested at the two imposed torque levels were assumed to coincide with the fatigue data for the modified Brugger samples. In this way, an “effective stress” (1170 and 1000 MPa) for each imposed torque could be determined. This procedure is shown for the open triangles in Fig. 10, a summary of the laboratory fatigue data shown previously, but without fatigue data points. At each of the two interpolated stress levels the average fatigue life for each of the other torque level/processing history conditions are plotted as shown in Fig. 10. This method of plotting allows the relative effects of the processing conditions to be directly compared for the two data sets. It should be noted that the fact that the pinion data appear to plot on the endurance limit line for the baseline modified Brugger samples is coincidental.

The finite lives of the modified Brugger samples are considered first. The slopes of the baseline, reheated and vacuum carburized conditions are approximately equal. However, the shot peened condition has a noticeably shallower slope. The finite lives for the baseline, reheated and vacuum carburized conditions are relatively close to each other with the reheat finite life shifted slightly to higher cycles.

Similar trends were observed for the pinions. For a constant imposed torque, the fatigue life of the baseline, reheated, and vacuum carburized samples were essentially equivalent. Furthermore, at either imposed torque, the shot peened samples exhibited significantly higher fatigue life. If lines, representative of the finite life region, were constructed by connecting the two data points for each pinion process condition, then the slopes could be compared to the finite life slopes observed with the modified Brugger samples. The trends in the slopes are similar to those displayed by the laboratory samples. Because of the analysis used, the baseline pinions were forced to have the same slope as the baseline modified Brugger samples. The fact that the reheated and vacuum carburized samples have similar slopes as the baseline condition for both specimen types is significant. The slope for the shot peened samples is significantly lower, again an observation consistent with the laboratory sample data.

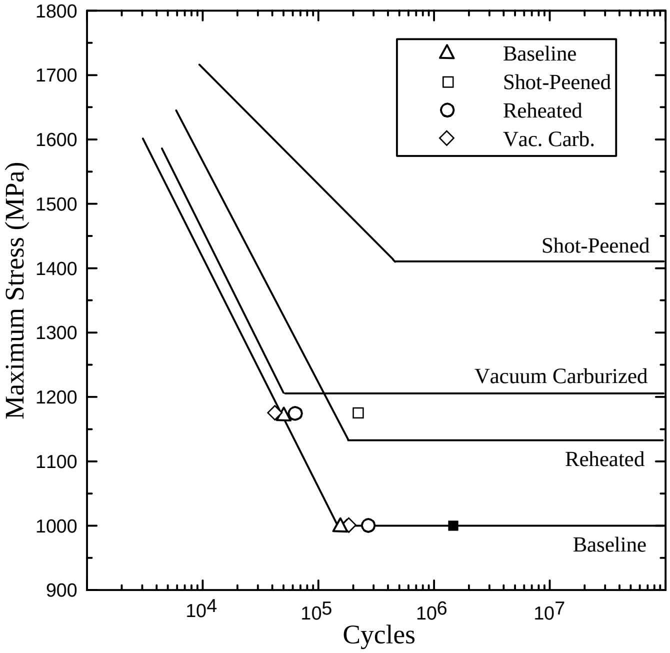

Figure 10. Modified Brugger S-N curves for all conditions with the B50 life of all pinion conditions at both stress levels. The solid shot peened sample represents the number of cycles to failure for one sample.

In comparing endurance limits, only the modified Brugger specimens were tested at levels low enough for all the specimens to run out (i.e. life greater than $2*10^6$ cycles). For the modified Brugger specimens, the shot peened condition had the highest endurance limit, followed by the vacuum carburized, reheated with the baseline having the lowest endurance limit.

While the pinions were only tested at two torque (i.e. stress) levels, a reasonable assumption can be made that the shot peened pinions tested at the lower torque level are near the endurance limit. At this level, some pinions were suspended at 2 million cycles and some failed by mechanisms other than root bending fatigue.

Assuming the shot peened pinions tested at the lower torque level are at the endurance limit, it would match the trend of the laboratory specimens that the shot peened samples have the highest endurance limits. Continuing with this assumption, it can be noted that the endurance limit of the shot peened pinions is lower than the modified Brugger samples. The reason for this difference is unknown. Some possibilities include an inherent difference due to the methodology used to plot the data shown in Figure 10, different surface roughness between the modified Brugger specimens which were chemically polished and the commercially produced pinions, or the difference in case/core hardness ratios for the relatively small laboratory specimens to the larger pinions. In addition, the pinions experience complex loading (bending/sliding contact forces) and the modified Brugger samples are only loaded in bending.

While no statements can be made about the endurance limits for the baseline, reheated and vacuum carburized pinions based on this study, if the trends stated above continue, the vacuum carburized pinions would have an endurance limit at a higher torque level than the reheated or baseline pinions. This would occur even with the finite lives being approximately the same.

The residual stress and retained austenite are constant among the different conditions with the exception of the shot-peened group. Because of shot peening, some of the retained austenite transformed to martensite, thus increasing the residual stress in the case. This is effective in increasing the performance of both sample types in both the finite and infinite life regions.

The grain size is constant between conditions with the exception of the reheated samples, which exhibited slight grain refinement. Despite the relatively small refinement in grain size, there is an improvement in both the endurance limit for the modified Brugger specimens and an improvement in the finite life of the pinions.

The intergranular oxidation is constant between sample types and conditions with the exception of the vacuum carburized group. The vacuum carburizing eliminated all intergranular oxidation. The removal of the intergranular oxidation does not appear to have affected the fatigue performance in the finite life region. The vacuum carburizing did improve the endurance limit of the modified Brugger specimens but there is no evidence of improvement in the pinion performance. Additional pinion testing at lower imposed torque levels would be required to fully characterize improvements.

CONCLUSIONS

1. A qualitative analysis can be made between laboratory specimens and commercially produced pinions. The trends suggested by the data are the same for both sample types and results obtained on modified Brugger samples can be used to interpret pinion fatigue performance.

2. All of the conditions showed improvement over the baseline for both sample types except the vacuum carburized condition showed no improvement in high cycle fatigue.

3. The shot peened samples have a shallower slope in the finite life region. This occurs in both the laboratory specimens and pinions.

4. The slopes and location of the baseline and vacuum carburized samples are the same for the laboratory specimens and pinions while both reheated groups are shifted slightly to higher cycle lives.

5. For the laboratory specimens, the shot peened condition had the highest endurance limit followed by the vacuum carburized condition, then the reheated with the baseline having the lowest performance.

6. The shot peened pinions tested at 2910 Nm were near the endurance limit. This was the only condition showing any evidence of approaching an endurance limit. The shot peened pinions having the highest endurance limit correspond with the modified Brugger data.

7. Processing by shot peening after carburizing was the only procedure that significantly increased the finite life and endurance limits in both the modified Brugger samples and the pinions.

8. The reheated condition for both sample types showed improvement in the finite life region with a slight shift to higher life. An improvement in the endurance limit over the baseline could only be confirmed with the laboratory specimens.

9. The vacuum carburized condition showed no improvement in the finite life region for both sample types. However, the laboratory samples did show a significant improvement in the endurance limit over the baseline condition.

ACKNOWLEDGMENTS

This work was supported by sponsors of the Advanced Steel Processing and Products Research Center, an Industry/University Cooperative Research Center. The Dana Corporation is gratefully acknowledged for supplying, carburizing and testing the pinions. One author (JJS) acknowledges the fellowship support of the Forging Industry Educational and Research Foundation.

REFERENCES

1. R.E. Cohen, D.K. Matlock, and G. Krauss, "Specimen Edge Effects on Bending Fatigue of Carburized Steel", Journal of Materials Engineering and Performance, vol. 1, no. 5, 1992, pp. 695-703.
2. J.P. Wise and D.K. Matlock, "Bending Fatigue of Carburized Steels: A Statistical Analysis of Process and Microstructural Parameters" SAE Technical Publication No. 2000-01-0611, SAE, Warrendale, PA., 2000.
3. J.P. Wise, D.K. Matlock and G. Krauss, “Microstructure and Fatigue Resistance of Carburized Steels”, Heat Treating: Proceedings of the 20th Conference, K. Funatani and G.E. Totten (Eds.), ASM International, Materials Park, Ohio, 2001, vol. 2, pp 1152-1161. Also published as “Bending Fatigue of Carburized Steels”, Heat Treating Progress, vol. 1, no. 4, 2001, pp. 33-41.
4. D. Medlin, G. Krauss, D.K. Matlock, K. Burris, and M. Slane, "Comparison of Single Tooth and Cantilever Beam Bending Fatigue Testing of Carburized Steel", SAE Technical Paper Series, No. 950212, SAE, Warrendale, PA. 1995.
5. R.S. Hyde, R.E. Cohen, D.K. Matlock, and G. Krauss, "Bending Fatigue Crack Characterization and Fracture Toughness of Gas Carburized SAE 4340 Steel", SAE Paper No. 920534, SAE, Warrendale, Pa. 1992.
6. T.P. Wilks, G.P. Cavallaro, and K.N. Strafford, “Fatigue of Surface-Hardened Gears”, Technomic Publishing Co., Inc., Surface Engineering. Process and Applications (USA), 1995, pp. 331-346, 1995.
7. G.P. Cavallaro, and C. Subramanian, “Fatigue of Case Hardened Gears”, Gear Technology (USA), vol. 16, no.2, pp. 18-23, Mar.-Apr. 1999.
8. G.P. Cavallaro, T.P. Wilks, C. Subramanian, K.N. Strafford, P. French, and J.E. Allison, “Bending Fatigue and Contact Fatigue Characteristic of Carburizing Gears”, Surface Engineering Research Group, University of South Australia, Surface Engineering (Australia), C319-C333, 1994
9. M. Widmark and A. Melander, “Effect of Material, Heat Treatment, Grinding and Shot Peening on Contact Fatigue Life of Carburized Steels”, International Journal of Fatigue (UK), vol. 21, no. 4, pp. 309-327, Apr. 1999.

10. W.E. Dowling Jr., W.T. Donlon, W.B. Coppel, R.A. Chernenkoff, and C.V. Darragh, “Bending Fatigue Behavior of Carburized Gear Steels: Four-Point Bend Test Development and Evaluation”, SAE Technical Paper No. 960977, SAE, Warrendale, Pa. 1996.