Effects of Gear Surface Parameters on Flank Wear

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Management Summary

Non-uniform gear wear changes gear topology and affects the noise performance of a hypoid gear set. The aggregate results under certain vehicle driving conditions could potentially result in unacceptable vehicle noise performance in a short period of time. This paper presents the effects of gear surface parameters on gear wear and the measurement/testing methods used to quantify the flank wear in laboratory tests.

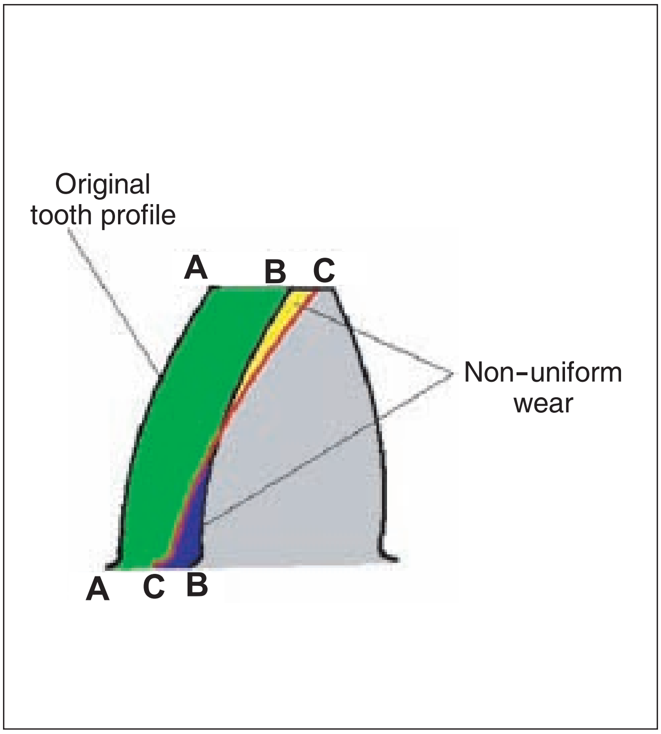

Figure 1—Gear wear.

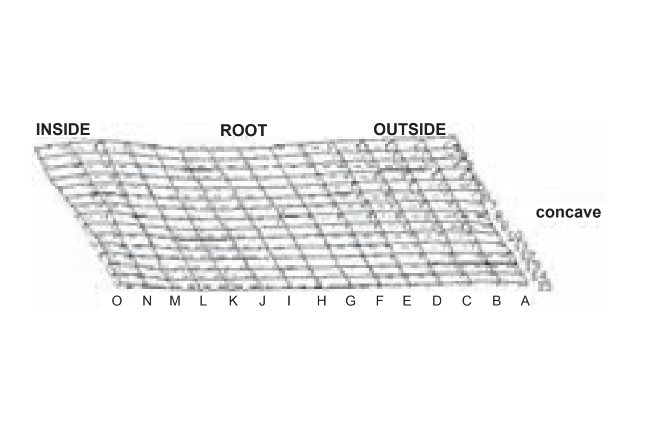

Figure 2—Pre-test pinion CMM results.

Introduction

Gear tooth profile, transmission error (TE), gear tooth surface finish determined by cutting and gear tooth surface finish determined by other processes are the factors considered in this paper. The measurements include transmission error, coordinate measurement machine (CMM), pattern rating and surface roughness pre- and post-test. An ASTM L37-based (Ref. 1) dynamometer test procedure is adopted for the wear study with good correlation to field samples. The laboratory test samples are established based on the design of experiment (DOE) considering the controlled factors. The effects and interaction between the controlled factors provided the information for product improvement. The results of this study are anticipated to significantly improve product reliability and customer satisfaction.

The laboratory test samples are established based on design of experiment (Ref. 2) in considering the controlled factors.

Gear wear can be separated into two different types: one is the uniform wear of tooth surface that doesn't affect noise performance; and the other is the non-uniform wear of tooth surface that affects noise performance. The differences are shown schematically in Figure 1. Curve AA represents the original tooth profile. A uniform wear will remove material from the tooth and create a new profile BB. Due to the non-uniform wear, the actual profile is as shown by curve CC. The discussions in this paper are focused on the non-uniform gear wear.

Gear Surface Parameters

The parameters considered for the DOE include:

- Gear tooth profile
- Gear set TE (transmission error)
- Gear tooth surface finish determined by cutting and lapping
- Gear tooth surface finish determined by processes post-hardening test

Other factors affecting uniform gear wear are identified in the test procedure development stage and are excluded from the DOE for reasons explained above.

Measurement Methods

Both objective and subjective ratings are used in pre-test and post-test stages for comparison purposes.

- TE measurements (single flank tester): The first-order drive side TEs are measured pre-test and post-test. The difference in TE measurements pre- and post-test (Delta TE) is an important indicator of the uneven wear. This TE measurement process is defined as a hardening test. It is performed after lapping and prior to final processing.
- CMM measurements: The sum of squared errors compared to a master is a good way of measuring non-uniform gear wear. The sum of squared errors is the sum of the square of error at each grid point— Sum of squared errors = $\Sigma_{i,\ j}$=1 to N (Deviation at row i and column j)^2.

The uniform gear wear is covered by the tooth thickness change from CMM measurement results. The ratio of the post-test sum of squared errors versus the pre-test number is an indicator of the non-uniform wear based on appropriate resolution of mesh points. Figure 2 shows a typical pinion measured on a CMM prior to gear wear testing. Figure 3

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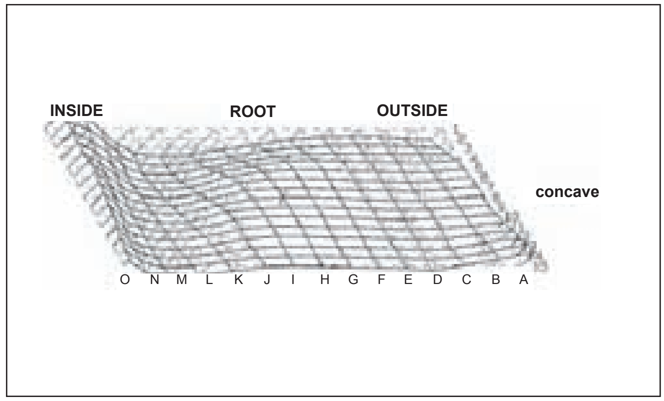

Figure 3—Post-test pinion CMM results with less non-uniform wear.

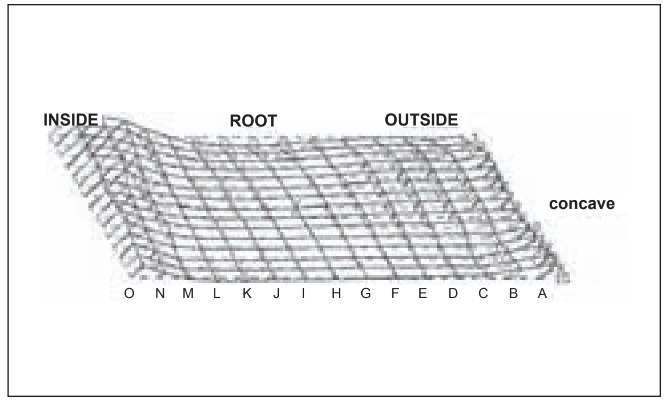

Figure 4—Post-test pinion CMM results with more non-uniform wear.

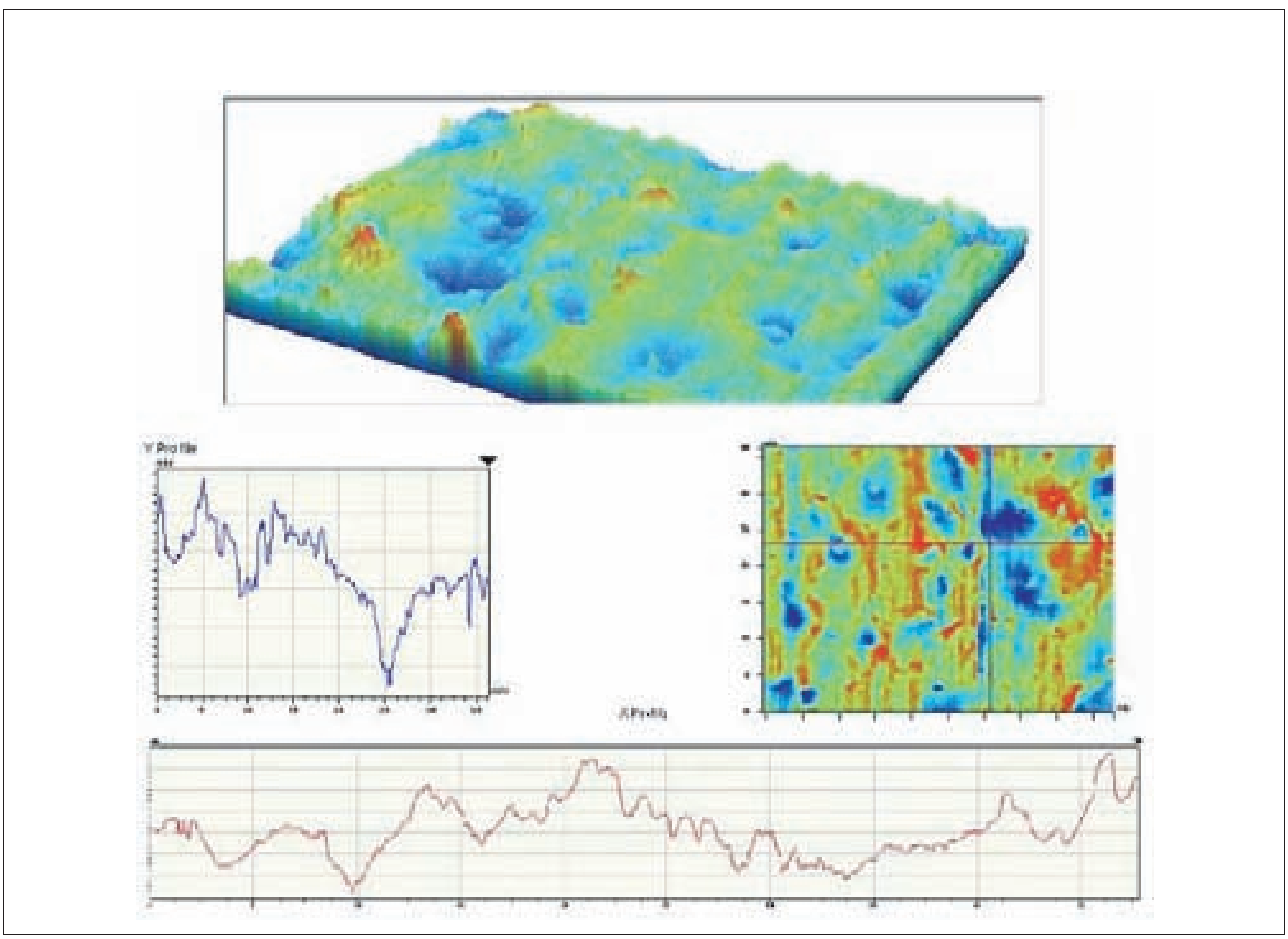

Figure 5—Typical gear tooth surface roughness.

shows a pinion with less non-uniform gear wear after wear testing. Figure 4 shows a pinion tooth surface with more non-uniform wear after wear testing.

- Pattern rating: This is a subjective rating helpful during development of the test procedure. The ratings range from 1 to 10 with 10 as the best pattern and 1 the worst. The patterns of the test gear set are taken and documented before and after testing. A qualified gear set representing the development has been used as the semi-masters. Patterns of pinion and gear rolled against semi-masters separately after testing are also documented to identify the wear on each part.
- Surface roughness: The pre-test and post-test surface finishes are part of the measurements. A typical hypoid gear tooth surface roughness is as shown in Figure 5. The three-dimensional surface can be established by scanning an area. The surface roughness numbers used in the DOE are along the tooth profile direction.

Test Method

The developed lab test is based on ASTM L37 dynamometer testing. The test load and speed were selected on the basis of testing several similar gear sets and observing the induced tooth wear. Care was taken to obtain a set of accelerated test parameters that induce only tooth wear and not any other type of system failure. It is a high-load, low-speed test intended to duplicate non-uniform gear wear with the gear contact pattern in Figure 8. A 24-hour test procedure is effective in differentiating the non-uniform gear wear of samples with different parameters. The test equipment is shown in Figure 6. A typical pinion after wear testing is shown in Figure 7.

A typical contact pattern from the field return is shown in Figure 8. The worn patterns are typically narrow in the profile direction and toward the root. Figure 9 and Figure 10 are the post-test patterns from the wear testing. The contact pattern in Figure 9 exhibits patterns typical of a worn gear set. A lesser amount of pattern narrowing and position movement along the profile direction can be observed in Figure 10.

DOE Samples

The dimensions of the tested gear set are listed in Table 1.

A full factorial of three controlled parameters is considered in the DOE. Each parameter is tested at high/low levels. A total of 16 samples were tested, with two duplicated samples for each test condition.

- 1st parameter: Gear set process post-hard test. Two different processes are considered in the DOE.

Figure 6—Test equipment.

Figure 7—A typical pinion post-test.

Figure 8—A typical contact pattern from field return.

Figure 9—Post-test contact pattern from wear test sample.

Level 1 is the current process post-hard test. Level 2 is the proposed new process.

- 2nd parameter: Gear set assembly backlash at high/low levels. This parameter is to control the pat tern position to simulate tooth profile change and TE change due to cutting and lapping processes.
- 3rd parameter: Gear set process pre-hard testing. Two levels of lapping processes are considered. Level 1 is the current production lapping cycles. The lapping cycles in Level 2 were modified to reflect different surface conditions.

Both pre-test and post-test measurements include TE, sum of squared error, contact pattern and surface roughness.

Test Results

Minitab was used for the test result analysis (Ref. 3). A Pareto chart is essentially a bar chart in which the bars are ordered from highest to lowest. A factor with a standardized effect of more than 2.306 is statistically significant. The main effect is the difference between the factor level mean and the overall mean. An interaction is present when the response at a factor level depends upon the level of other factors.

The hypoid pinion is the part showing the most significant non-uniform wear. This is shown in the patterns rolled with the semi-master. Figure 11 shows the pattern rolled between a tested gear and the semi-master pinion. It doesn't show obvious pattern narrowing or position change, as in Figure 9. Figure 12 shows the pattern rolled between a tested pinion and the semi-master gear. It is similar to that in Figure 9 with narrowing pattern and position change. The patterns rolled with semi-masters suggest that the test pinions are the primary source of non-uniform wear. CMM measurements also confirm the trend, as shown in the sum of squared errors.

All the test data are included in Figure 13. "Delta TE" is the difference between post-test TE and pre-test TE divided by pre-test TE. "Delta Pin Surf" represents the difference between post-test surface roughness and pre-test surface roughness for the pinion divided by the pre-test number. "Delta Gear Surf" presents the numbers for the gear with the same definition as the pinion. "Pin Sum of Sqrd" is the ratio of the post-test sum of squared errors divided by the pre-test sum of squared errors for the pinion. "Gear Sum of Sqrd" is the ratio of the post-test sum of squared errors divided by the pre-test sum of squared errors for the gear. The numbers were normalized to have a commonality for comparison between different measurements.

The most significant factor in this study is the post-process after hard testing. Gear sets from process two show better results than gear sets from process one in the pinion sum of squared errors ratio, Delta TE and subjective pattern ratings (Figure 10 versus Figure 9) in Figure 13. Delta pinion surface finish, Delta gear surface finish and gear sum of squared errors ratio are not closely related to the post-test pattern, as shown in Figure 13.

The Pareto charts, main effects plots, and interaction plots

continued

Figure 10—Post-test contact pattern from wear test sample with less severity.

Table 1 Tested Gear Set

Item	Number
Ratio	4.88
Diametral pitch, 1/in.	3.2
Offset, in.	1.4
Pitch diameter, in.	12.2

Figure 11—Post-test contact pattern between tested ring gear and semi-master pinion.

Figure 12—Post-test contact pattern between tested pinion and semi-master ring gear.

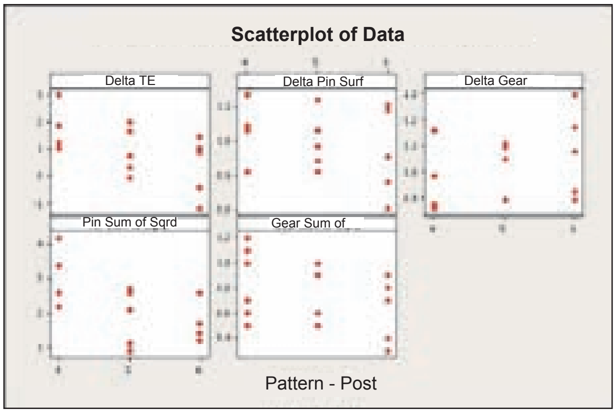

Figure 13—Scatter plot of all data—delta TE; delta pinion surface roughness; delta gear surface roughness; pinion sum of squared errors; and gear sum of squared errors.

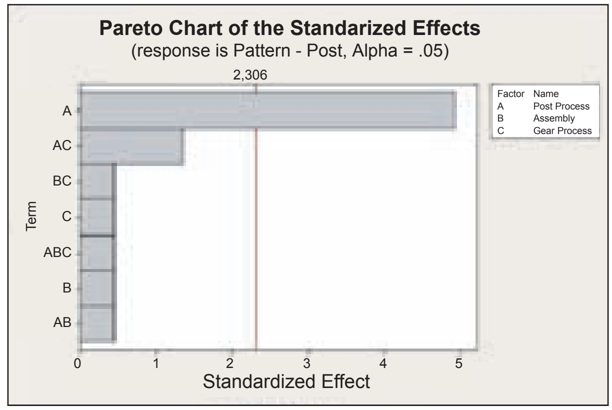

Figure 14—Post-test pattern rating Pareto chart.

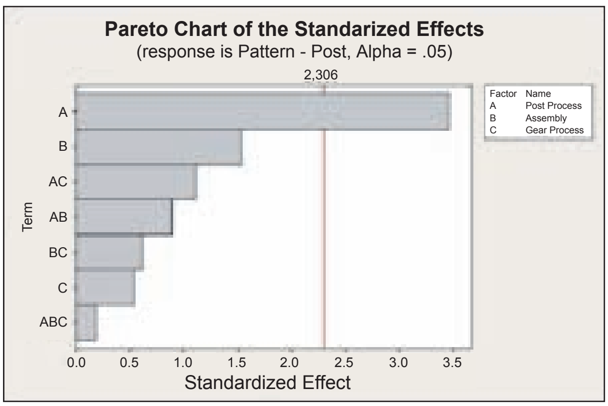

Figure 15—Pinion sum of squared errors ratio Pareto chart.

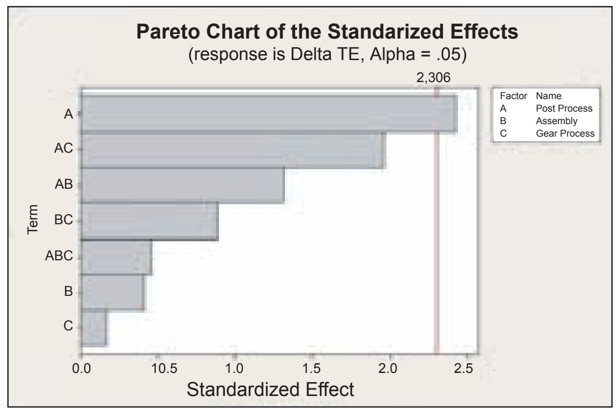

Figure 16—Delta TE Pareto chart.

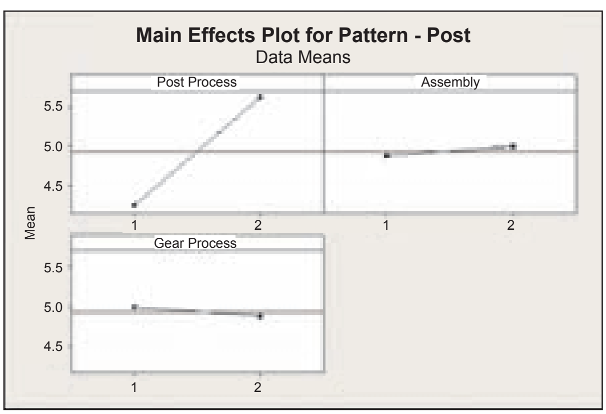

Figure 17—Post-test pattern rating main effects.

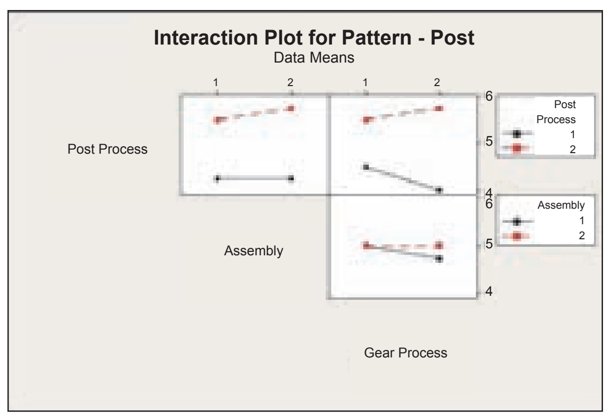

Figure 18—Post-test pattern rating interaction.

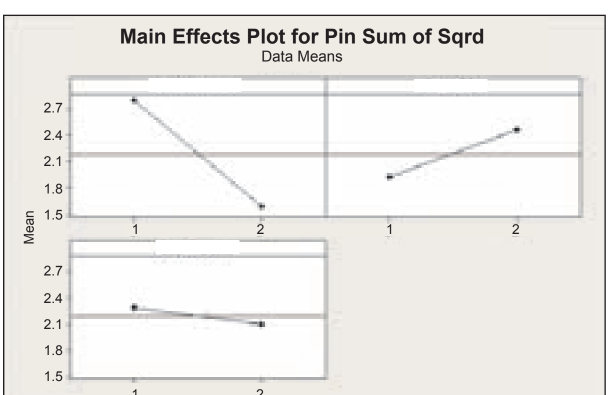

Figure 19—Pinion sum of squared errors ratio main effects.

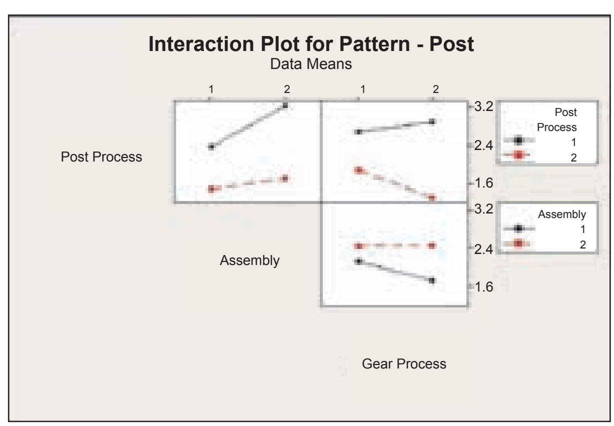

Figure 20—Pinion sum of squared errors ratio interaction.

for post-test pattern rating, pin sum of squared errors and Delta TE are shown in the following figures. The factors shown in the figures are abbreviated due to software limitations. "Post process" refers to the gear set process post-hardening testing. "Assembly" means gear set assembly backlash at high/low levels. "Gear Process" is the gear set process pre-hardening testing.

The post process after hardening testing is clearly the most significant factor that affects the results. The Pareto charts in Figure 14, Figure 15 and Figure 16 demonstrate that only factor A is statistically significant in the effects of post-test pattern rating, pinion sum of squared errors and Delta TE.

The plots in Figures 17, 19 and 21 show "Post-Process" as the most significant factor for post-test pattern rating, pinion sum of squared errors ratio and Delta TE. Figures 18, 20, and 22 indicate different level of interactions between "Post-Process," "Assembly" and "Gear Process." The amount of interaction is not significant enough to change the importance of the factors.

Conclusion

The test procedure and measurement methods discussed in this paper prove to be a feasible approach in determining the cause of non-uniform gear wear within acceptable time constraints. The effects and interaction between controlled factors provided the information for product improvement without specifically identifying the root causes of non-uniform gear wear. The action resulted from this study is anticipated to significantly improve product reliability and customer satisfaction. Further studies with enhanced control of factors can contribute to the identification of non-uniform gear wear phenomena in the future.

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2. Bhote, Keri R. and Ade K. Bhote. "World-Class Quality using Design of Experiments to Make It Happen," *American Management Association*, 2000.
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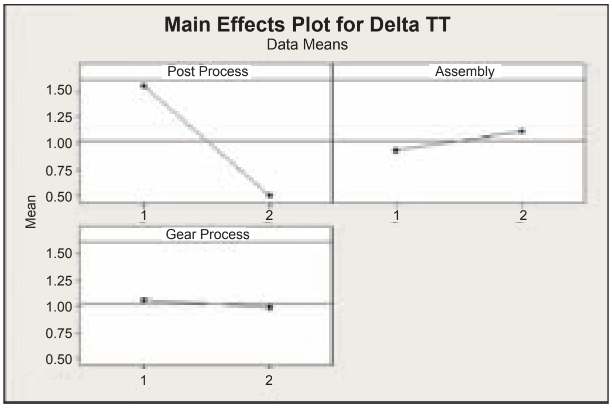

Figure 21—Delta TE main effects.

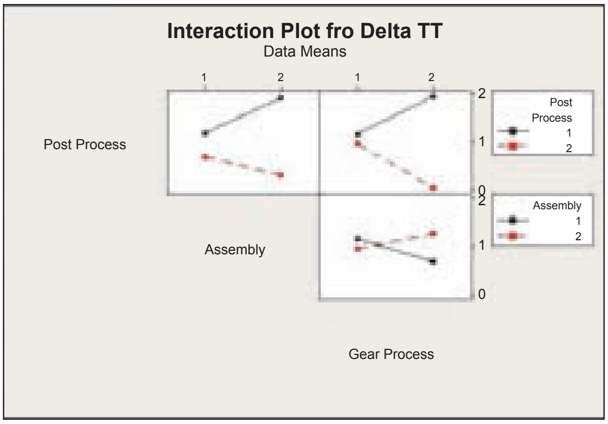

Figure 22—Delta TE interaction.

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__Hai Xu__ is currently working in the Gear Engineering Department of Dana Holding Corporation in Kalamazoo, Michigan. He is responsible for design, development and research of axle gearings with main interests in hypoid gearing fatigue life, noise, wear, friction and efficiency. He obtained a masters of science degree in mechanical engineering from the University of Michigan-Dearborn in 2002, and a Ph.D. in mechanical engineering from The Ohio State University in 2005. He is a member of ASME, SAE and Sigma Xi.