The Effects of Pre-Rough Machine Processing on Dimensional Distortion During Carburizing

Gregory Blake

Management Summary

A study was conducted to isolate the influence of pre-rough machine processing on final dimensional distortion. Methods are discussed to aid process development and minimize dimensional change during carburizing. The study examines the distortion during carburizing between five possible raw materials starting conditions. Coupons were used and manufactured from each population of material processing. All coupons were carburized and hardened at the same time. Dimensions were made before and after carburizing using a scanning coordinate measurement machine. The results show the dimensional distortion during carburizing increased with mechanical and thermal processing.

This article presents the methods and results of an empirical study that was conducted to aid process development of a carburized aerospace gear. The objective of the study was to determine the contribution of pre-machining material processing on dimensional distortion during carburizing. Five possible raw material starting conditions were evaluated. The five pre-rough machining conditions studied were: (i) normalized AMS6265 bar stock, (ii) hardened and tempered (core-treated) AMS6265 bar stock at 1,725°F, (iii) hardened and tempered (core-treated) AMS6265 bar stock at 1,550°F, (iv) normalized AMS6260 forging, and (v) hardened and tempered (core-treated) AMS6260 forging at 1,725°F.

Cost, time, and lurking variables were minimized by use of a standard distortion coupon in place of actual aerospace gears. The coupon design is shown in Figure 1. H. French used this type of coupon to study dimensional distortion during repeated quenching (Ref. 1). French's coupon was scaled as necessary for use in this study. The diametrical changes of the coupon indicate the volume changes during hardening. The width of the slot reflects the magnitude of internal stresses set up by the volumetric changes (Ref. 1). French showed that dimensional distortion increased as the number of quench cycles increased. The distortion coupon gap width increased with each quench cycle, thus indicating that residual stresses were increasing with each thermal cycle.

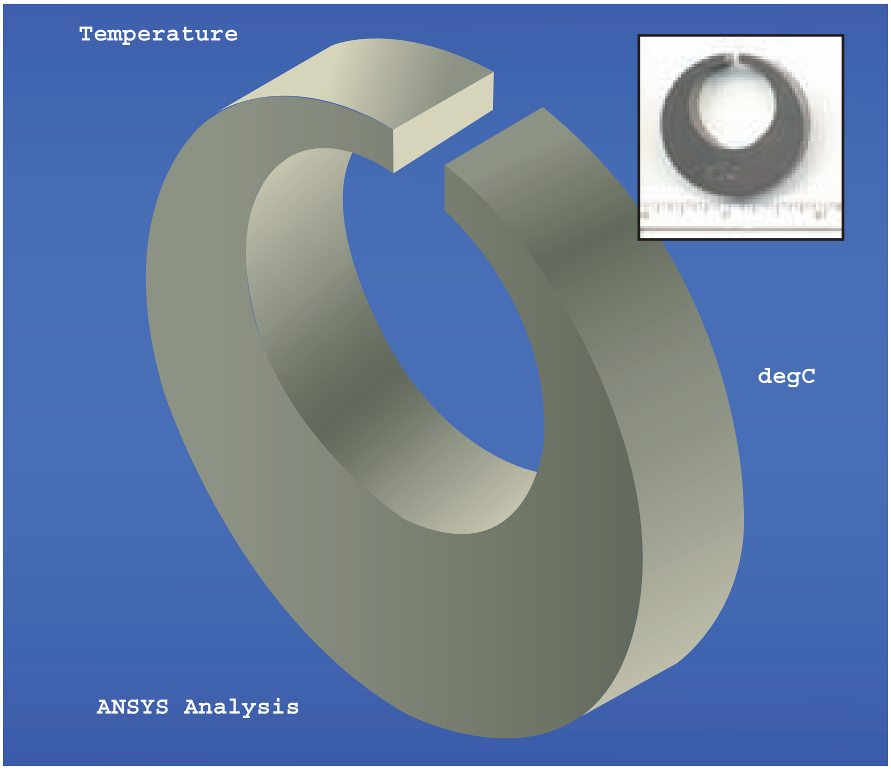

Figure 1—Distortion coupon, GR-0010.

The hypothesis is that dimensional distortion increases along with the thermal and mechanical processing of the raw material prior to machining. The implication is that dimensional distortion can be influenced before the raw material enters the machining process.

Precarburizing process variables and their influence on dimensional distortion were studied previously. The Instrumented Factory for Gears (INFAC) studied the effects of processing variables prior to carburizing. The INFAC study evaluated residual stresses induced by turning and hobbing and their contribution to dimensional distortion. Mechanical and thermal processing of the raw material, however, was not included in the study.

Background and Literature Review

A dedicated manufacturing cell to produce small aerospace gears was designed and implemented. The design of the manufacturing cell and process was to minimize lead time and cost. The shaping process was used to generate the spline and gear teeth. The resultant gear and spline surface integrity produced by the newly designed process was deemed unacceptable due to machining tears that would not clean up during gear grinding. An example of the post-shaped tooth surface is shown in Figure 2.

Surface integrity is the description and control of the many possible alterations produced in a surface layer during manufacturing. Surface integrity can be evaluated based on a minimum data set. The data set is composed of surface texture, macrostructure, microstructure, and microhardness alterations (Ref. 2). The data set for macrostructure will include surface imperfections such as pits, tears, and/or laps.

The raw material selected for use in the new manufacturing cell was normalized bar stock, which was within the engineering requirements of the finished gear. The soft normalized bar stock was viewed as a good choice for machinability. Many literature sources supported this conclusion. Mott defined machinability as being related to the ease with which a material can be machined with reasonable tool life (Ref. 5). Verzahntechnik Lorenz (Ref. 6) and Cluff (Ref. 7) indirectly used a similar definition stating that machinability (reasonable tool life) decreases as material hardness increases. The two key terms are "ease of material removal" and "reasonable tool life." An indication of expected surface integrity is not present using these definitions of machinability.

Material hardness can be used as a machinability indicator due to the close relationship between hardness and microstructure (Ref. 8). However, hardness is an accurate representation of machinability only for similar microstructures. Mullins states that a tempered martensite matrix will exhibit superior machinability to a pearlite matrix of similar hardness (Ref. 8). Woldman studied microstructure and machinability and noted that a microstructure selected for long tool life would not necessarily produce good surface integrity (Ref. 9).

Based on literature and experience, a tempered martensitic microstructure was desired to produce the required surface integrity. The addition of the hardening and tempering operation was viewed as a risk to changing the dimensional distortion during carburizing and hardening.

A great amount of manufacturing development had been done implementing the new cell. The dimensional distortion during carburizing and hardening had been established and had been determined acceptable and manageable. The addition of a hardening and tempering operation prior to rough machining was viewed as an addition to cost, lead time, and risk of increased dimensional distortion during carburizing. Increased dimensional distortion would then require more process development time and cost.

Problem Statement

Common ground: Aerospace power transmission components must be manufactured to the highest quality standard while minimizing cost of nonquality.

Destabilizing condition: Gear tooth surfaces inconsistently have poor surface integrity ("tears") present after finish flank grinding. The surface defects are produced during the semi-finishing, prehardening operation and result in deviated, reworked, and/or scrapped parts.

Contributing factor: Aerospace gears are expensive and have long lead times. A study of many variables is not always practical using actual gears.

Problem: The shaping machine used in the manufacturing cell has limited cutting parameters. Literature suggests that hardening and tempering the material prior to any machining will improve the surface integrity during shaping. The material structure is then martensitic, and hardness ranges from Rc 25 to Rc 32. However, literature also suggests that this fix could negatively influence dimensional distortion during hardening.

Solution: Material samples made of different microstructure and hardness will be fabricated and tested. Paired data studies statistically analyzing dimensional distortion will be performed on coupons of similar size and process.

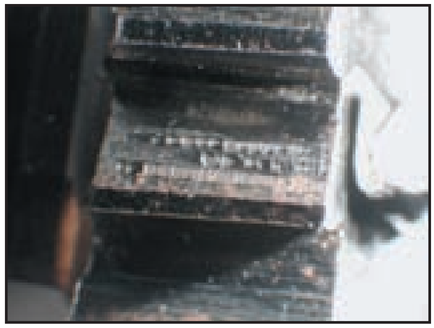

Figure 2—Gear tooth surface, post-shaping (Ref. 3).

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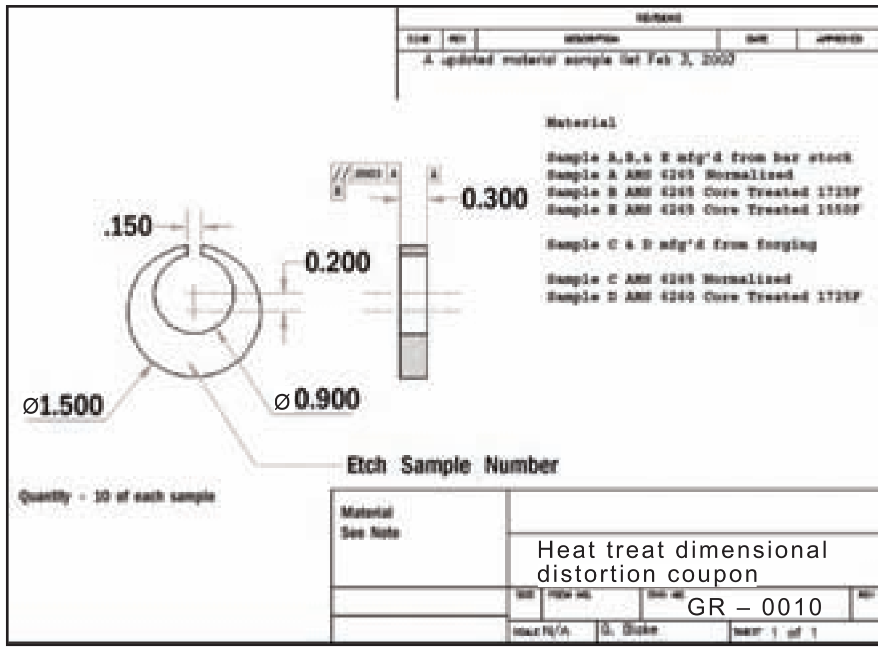

Figure 3—Detailed specimen drawing (units = inches).

Assumptions

The material samples are assumed to fully represent their population. For example, a group of normalized material samples is assumed to represent all normalized material.

The change in coupon gap width is assumed to represent the relative dimensional distortion of an actual gear.

Methods and Procedures

This section contains the details of coupon manufacturing and processing. Standard distortion coupons were manufactured for each population as shown in Figure 1. The dimensions of the coupon were proportional to the gear being developed and are shown in Figure 3. Coupons from each population were machined,

Table 1—Specimen Populations.					
Material	Form	Pre-Machining Heat Treatment	Quantity	Expected Structure	Identification
AMS6265	Barstock	Normalized	10*	Pearlite in Ferrite Matrix	A
AMS6265	Barstock	Normalized + Harden at 1,725°F	10*	Pearlite in Ferrite Matrix	B
AMS6260	Forging	Normalized	10*	Pearlite in Ferrite Matrix	C
AMS6260	Forging	Normalized + Harden at 1,725°F	10*	Tempered Martensite	D
AMS6265	Barstock	Normalized + Harden at 1,550°F	10*	Tempered Martensite	E
*One additional specimen was manufactured for metallurgical evaluation.					

Table 2—Hardening and Tempering Process at 1,725°F.	
Operation	Operation Description
10	Load
20	Core Harden
	Temperature 1,725°F
	Time at temperature: 1 hour minimum
	Atmosphere: Endogas
	Quench in 110–190°F oil to 200°F max. part temperature
25	Wash
30	Load
40	Temper to BHN 258–301
	Temp. (ref.) 980°F
	Time at temperature: 2 hours minimum
50	Unload
60	Clean
69	Inspect

Table 3—Hardening and Tempering Process at 1,550°F.	
Operation	Operation Description
10	Load
20	Core Harden
	Temperature 1,550°F
	Time at temperature: 1 hour minimum
	Atmosphere: Endogas
	Quench in 110–190°F oil to 200°F max. part temperature
25	Wash
30	Load
40	Temper to BHN 258–301
	Temp. (ref.) 980°F
	Time at temperature: 2 hours minimum
50	Unload
60	Clean
69	Inspect

Table 4—Manufacturing Process of Coupons.	
Operation	
10	Heat treat as necessary
20	Rough turn outer diameter, leaving grind stock
30	Finish grind outer diameter
40	Rough cut over all length, leaving grind stock
50	Stamp ID
60	Finish grind face
70	Finish grind second face
80	EDM inner diameter and slot
90	Stress relieve 300°F minimum 1 hour
100	CMM inspection
110	Carburize (carburizing and hardening process in separate table)
120	CMM inspection
130	Harden and temper
140	CMM inspection

stress relieved, carburized, and hardened together. The coupons were randomly located in the carburization furnace and quench basket. A summary of the populations is shown in Table 1. A sample size of 10 was used with one additional sample used for metallurgical evaluation. The samples' letter designations will be used from this point on to identify the populations. The raw material requiring hardening and tempering was heat treated in-house as listed in Table 2 and Table 3 prior to any machining. The normalizing process was done per the AMS specification prior to receiving the material. The manufacturing and inspection stages of the coupons are listed in Table 4. The coupons were carburized and hardened using a cycle common to the actual gear (see Table 5).

Dimensional measurements. A Zeiss Prismo scanning coordinate measuring machine (brass tag #253685) was used to perform all measurements. The outside diameter, inside diameter, and the gap width of every coupon was measured before carburizing, after carburizing, and after hardening. Each time, the outside diameter and etched face were scanned and set as reference. The gap width was measured at a constant radius of 0.7000 inches from the reference center. All measurements were taken in a plane 0.1500 inches (half overall length) from the reference face using a 0.054" diameter probe. The coupons were soaked in mineral spirits, wiped dry and rinsed with alcohol before each measurement. The cleaned coupons were placed in the CMM room 24 hours before measurement to thermally soak and stabilize. The CMM room temperature is held at 69°F +/– 2°F. The actual measurements are contained in Appendices A–D. A sample inspection report is in Appendix D.

Findings

This section contains all of the data and findings collected during the study. Data collected includes characterization of the pre-carburization microstructure and dimensional measurements.

Pre-carburization microstructure. To document the pre-carburized material, an extra coupon was manufactured from each population for metallurgical evaluation. The evaluation was performed after finish machining and before carburizing. The chemistry of Sample E is not reported in Table 7. The sample was lost during the metallurgical evaluation process. The hardness (see Table 6), chemistry (see Table 7), and microstructure (see Figures

Table 5—Carburize and Hardening Process.

Operation	Operation Description
10	Carb:
	0.030" – 0.035" cycle
	1,700°F, 1.5 hrs.
	1,700°F, 1.15%C, 5 hrs.
	1,700°F, 0.85%C, 2 hrs.
	Furnace cool to 1,000°F
	Air cool to ambient
20	Harden: 1,500°F, 0.85%C, 2 hrs.
	Quench in 110–190°F oil for 10 minutes
30	Temper: 300°F, 3 hrs.
40	Stabilize: –100°F, 3 hrs.
50	Temper: 300°F, 3 hrs.

Table 6—Pre-Carburization Hardness (Refs. 10–11).

	Hardness BHN 3,000kg Load				
Face location	Sample A	Sample B	Sample C	Sample D	Sample E
Center	207	302	255	285	269
Near O.D.	207	285	248	302	269

Table 7—Pre-Carburization Chemistry in Weight % (Ref. 10).

	Location	C	Mn	Cr	Ni	Mo	P	S	Si	Al	Cu
A	Center	0.080	0.510	1.220	3.180	0.080	0.012	0.006	0.260	0.010	0.020
A	Near O.D.	0.080	0.510	1.230	3.170	0.080	0.013	0.006	0.280	0.010	0.020
B	Center	0.100	0.470	1.240	3.220	0.090	0.012	0.006	0.270	0.010	0.020
B	Near O.D.	0.090	0.620	1.250	3.200	0.080	0.012	0.006	0.270	0.010	0.020
C	Center	0.130	0.660	1.450	3.120	0.090	0.016	0.006	0.310	0.050	0.010
C	Near O.D.	0.130	0.640	1.430	3.120	0.080	0.014	0.006	0.270	0.040	<0.01
D	Center	0.080	0.630	1.300	3.050	0.110	0.014	0.018	0.230	0.010	0.150
D	Near O.D.	0.070	0.620	1.300	3.020	0.100	0.014	0.020	0.250	0.020	0.150
E	Center	Sample Lost									
E	Near O.D.										

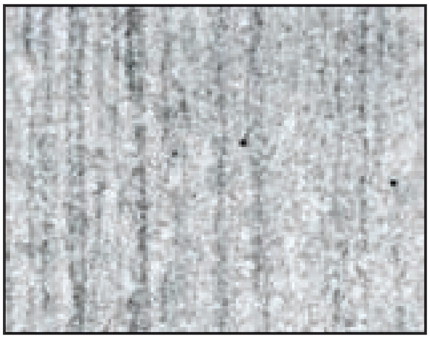

Figure 4—Sample A center microstructure 100X, 5% nital etch (Ref. 10).

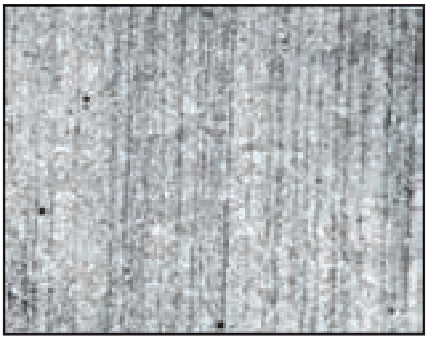

Figure 5—Sample A near OD microstructure 100X, 5% nital etch (Ref. 10).

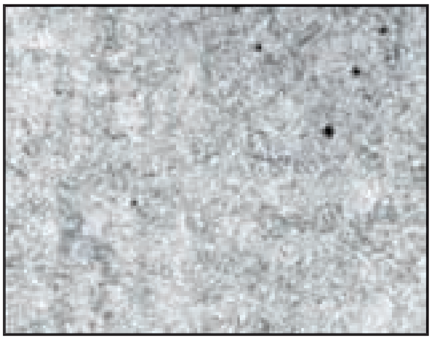

Figure 6—Sample B center microstructure 100X, 5% nital etch (Ref. 10).

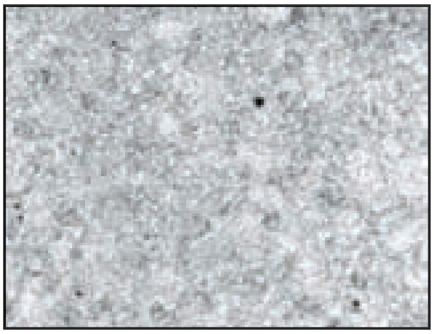

Figure 7—Sample B near OD microstructure 100X, 5% nital etch (Ref. 10).

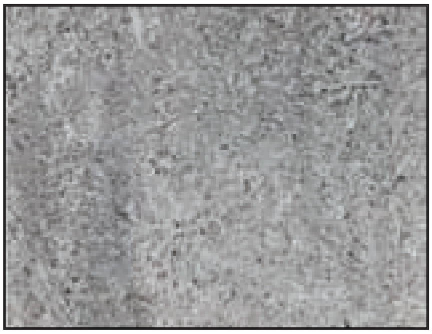

Figure 8—Sample C center microstructure 100X, 5% nital etch (Ref. 10).

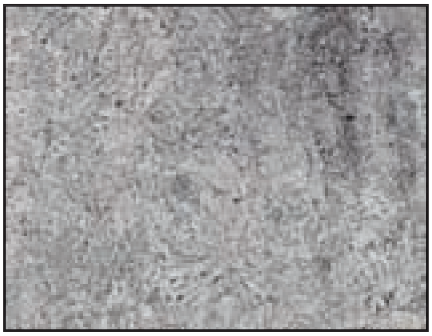

Figure 9—Sample C near OD microstructure 100X, 5% nital etch (Ref. 10).

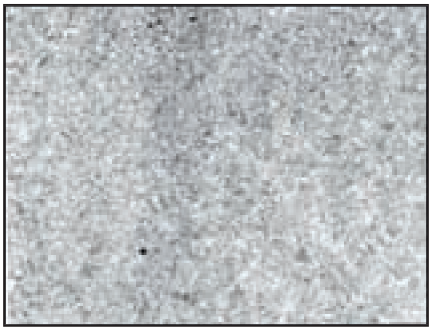

Figure 10—Sample D center microstructure 100X, 5% nital etch (Ref. 10).

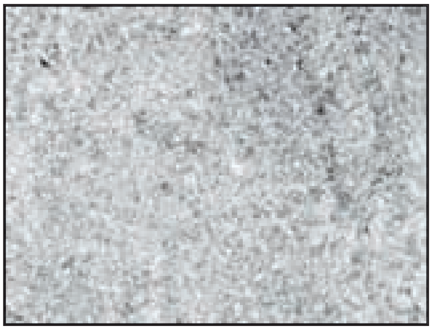

Figure 11—Sample D OD microstructure 100X, 5% nital etch (Ref. 10).

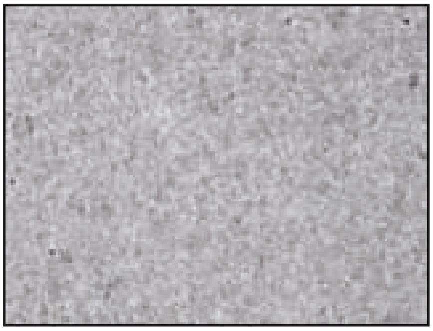

Figure 12—Sample E center microstructure 100X, 5% nital etch (Ref. 11).

Table 8—Descriptive Statistics of Pre-Carburization Gap Width Measurement.

	Pre-Carb Gap Width (inches)				
	A	B	C	D	E
Mean	0.1508	0.1525	0.1509	0.1520	0.1516
Standard Error	0.0001	0.0002	0.0001	0.0001	0.0001
Median	0.1509	0.1526	0.1508	0.1518	0.1517
Standard Deviation	0.0004	0.0005	0.0003	0.0004	0.0003
Sample Variance	1.32E–07	2.48E–07	8.00E–08	1.47E–07	9.90E–08
Range	0.0014	0.0017	0.0008	0.0012	0.0010
Minimum	0.1500	0.1513	0.1506	0.1513	0.1511
Maximum	0.1514	0.1531	0.1514	0.1525	0.1521
Sum	1.5081	1.5251	1.3579	1.5196	1.5161
Count	10	10	9	10	10
(95.0%) Conf.	0.0003	0.0004	0.0002	0.0003	0.0002

Table 9—Descriptive Statistics of Post-Carburization Gap Width Measurements.					
	Post-Carburization Gap Width (inches)				
	A	B	C	D	E
Mean	0.1496	0.1543	0.1504	0.1533	0.1504
Standard Error	0.0002	0.0002	0.0001	0.0003	0.0002
Median	0.1494	0.1543	0.1504	0.1537	0.1507
Standard Deviation	0.0005	0.0007	0.0004	0.0009	0.0008
Sample Variance	2.82E–07	4.54E–07	1.49E–07	9.02E–07	6.07E–07
Range	0.0015	0.0022	0.0012	0.0034	0.0025
Minimum	0.1491	0.1529	0.1500	0.1509	0.1488
Maximum	0.1506	0.1551	0.1512	0.1542	0.1513
Sum	1.4960	1.2344	1.3539	1.5328	1.5039
Count	10	8	9	10	10
(95.0%) Conf.	0.0004	0.0006	0.0003	0.0007	0.0006

Table 10—Descriptive Statistics of Post-Hardening Gap Width Measurements.					
	Post-Hardening Gap Width (inches)				
	A	B	C	D	E
Mean	0.1532	0.1581	0.1550	0.1587	0.1541
Standard Error	0.0006	0.0006	0.0003	0.0004	0.0005
Median	0.1537	0.1581	0.1553	0.1587	0.1540
Standard Deviation	0.0018	0.0017	0.0010	0.0012	0.0017
Sample Variance	3.33E–06	2.84E–06	1.07E–06	1.36E–06	2.81E–06
Range	0.0055	0.0047	0.0034	0.0040	0.0047
Minimum	0.1496	0.1555	0.1525	0.1567	0.1520
Maximum	0.1550	0.1603	0.1559	0.1607	0.1568
Sum	1.5316	1.2650	1.3946	1.5867	1.5405
Count	10	8	9	10	10
(95.0%) Conf.	0.0013	0.0014	0.0008	0.0008	0.0012

4–12) were evaluated on the etched face side of the coupon in two radial locations, center and near the outer diameter.

Dimensional measurements and descriptive statistics. Measurements were recorded before carburization, after carburization, and after hardening. Details of the measurement method are in the Methods and Procedures section. Serial numbers B5 and B6 were lost during carburization and serial number C10 was scrapped during manufacturing (see Appendix B). Descriptive statistics of the pre-carburization, post-carburization, and post-hardening measurements are listed in Tables 8–10. The actual measurements are shown in Figure 13. Descriptive statistics of the paired difference between

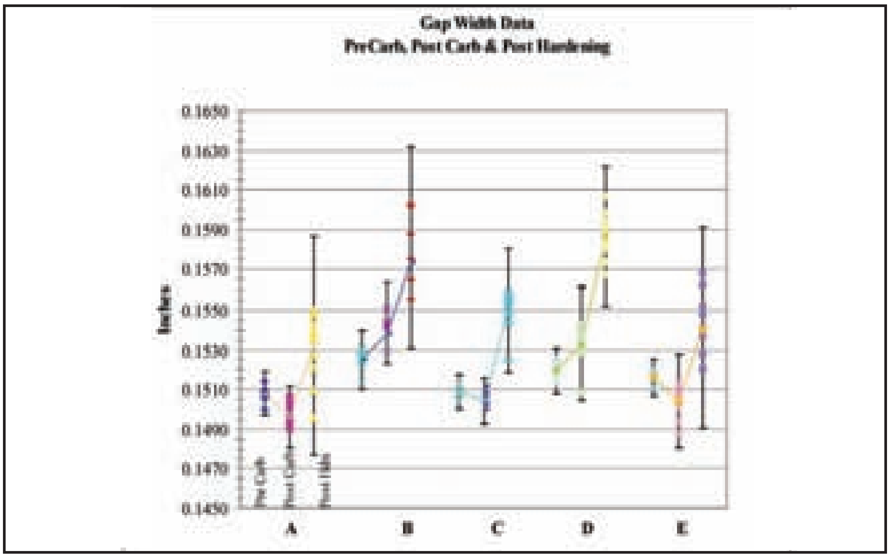

Figure 13—Gap width measurements after each processing step of carburizing and hardening.

Table 11—Descriptive Statistics of Paired Difference Gap Width Measurements.					
	Paired Difference (Pre-Carburization/Post-Hardening) Gap Width (inches)				
	A	B	C	D	E
Mean	–0.0023	–0.0054	–0.0041	–0.0067	–0.0024
Standard Error	0.0006	0.0006	0.0003	0.0004	0.0005
Median	–0.0030	–0.0053	–0.0045	–0.0068	–0.0024
Standard Deviation	0.0019	0.0016	0.0010	0.0013	0.0017
Sample Variance	3.76E–06	2.47E–06	9.97E–07	1.76E–06	2.81E–06
Range	0.0056	0.0044	0.0030	0.0045	0.0051
Minimum	–0.0042	–0.0075	–0.0048	–0.0087	–0.0051
Maximum	0.0014	–0.0031	–0.0018	–0.0042	0.0000
Sum	–0.0235	–0.0434	–0.0367	–0.0671	–0.0245
Count	10	8	9	10	10
(95.0%) Conf.	0.0014	0.0013	0.0008	0.0009	0.0012

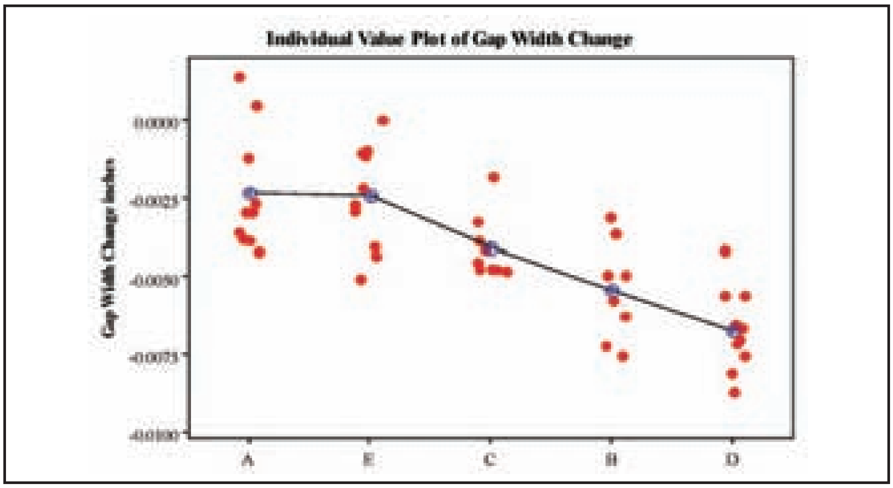

Figure 14—Data plot of gap width paired distance.

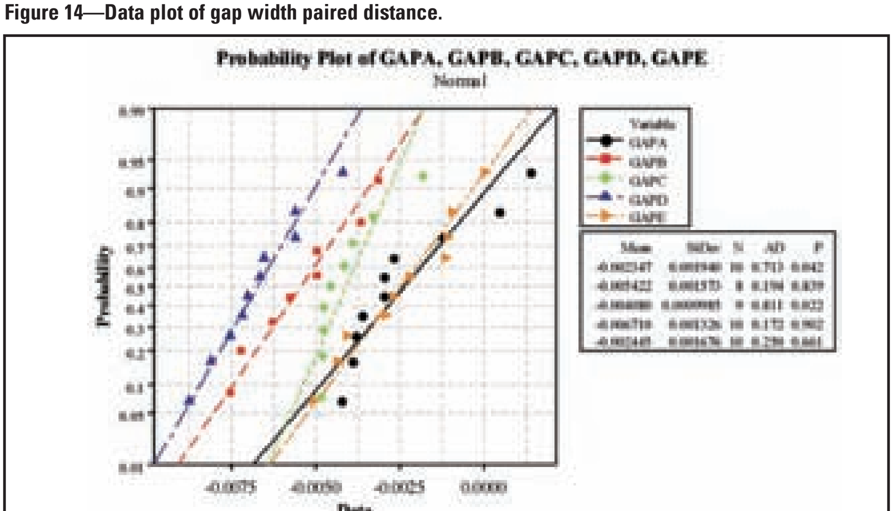

Figure 15—Probability plot of paired gap width distance.

Table 12—Gap Width Paired Difference Analysis of Variance (ANOVA).						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.000140	4	0.000035	14.674827	0.00000014	2.594263
Within Groups	0.000100	42	0.000002			
Total	0.000240	46				

pre-carburization and post-hardening are listed in Table 11. The mean paired difference values are shown in Figure 13.

Paired difference. The pre-carburization and post-hardening gap measurements were paired to enable a relative comparison. The gap width difference is reported as initial minus final. Thus, a change resulting in an increased gap width is reported as a negative value.

Graphical checks of the gap width change data were performed and shown in Figures 14 and 15. The checks include an individual data plot and a normal probability plot. Notice that the paired difference measurements were sorted based on each population's mean value and plotted.

An analysis of variance (ANOVA) was performed to compare the five population means (see Table 12). Formally, the data analysis is stated as:

H0: $\mu A = \mu B = \mu C = \mu D = \mu E$

H1: μA, μB, μC, μD and μE are not all equal

$\alpha = 0.05$

The F statistic is greater than the F critical value. Therefore, the null hypothesis is rejected, and the alternate accepted. The ANOVA identifies if difference is present between any of the mean values. A multiple comparison procedure is required to determine in what way they are not equal. A Fisher's Least Square Difference (LSD) test was performed at an individual $\alpha = 0.05$ to determine which of the population means were significantly different from each other. The results are listed in Table 13.

An upper value equal to or greater than zero indicates that the population is significantly less (greater distortion) than the population subtracted from. A summary of the LSD results is listed in Table 14.

Discussion

The gap width change was used to indicate differences in dimensional distortion during carburizing and hardening between five different raw material mechanical and thermal processes. Statistical analysis of the gap width change provides the following:

1.) Coupons manufactured from hardened and tempered barstock and forgings at 1,725°F had the greatest gap width change.

2.) Coupons manufactured from normalized barstock had the smallest gap width change. Coupons manufactured from normalized forgings had significantly more gap width change than those made from normalized barstock.

3.) Coupons manufactured from barstock hardened and tempered at 1,725°F had significantly more gap width change than those made from barstock hardened and tempered at 1,525°F.

4.) Coupons manufactured from barstock hardened and tempered at 1,550°F had no significant difference in gap width change than those made from normalized barstock.

The barstock used to manufacture coupons was from a common heat lot. Also, the forgings used were from a common heat lot. Additional heat lots could change the mean and/or scatter gap width change. It is recommended that future studies include multiple heat lots of materials. It is further recommended that future studies include residual stress measurements prior to carburization and hardening.

Based on the results of this study, hardened and tempered barstock at 1,550°F was selected. The surface integrity of the shaped gear and spline teeth improved greatly. Pre- and post-heat treat data collected from actual gears showed no change to the heat treat distortion.

See pages 42-44
for the Appendices
and References.

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Table 13—Fisher's Least Square Difference Test (units = inches).

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Fisher 95% Individual Confidence Intervals
All Pairwise Comparisons among Levels of Process
Simultaneous Confidence Level = 72.47%
Process = A substracted from:

Process    Lower      Center     Upper
E        –0.001493  –0.000098   0.001296
C        –0.003165  –0.001733  –0.000300
B        –0.004554  –0.003076  –0.001597
D        –0.005757  –0.004363  –0.002969

Process  ---------+---------+---------+---------+
E                (----*---)
C            (----*----)
B         (----*----)
D  (---  *----)
     ---------+---------+---------+-----------+
          –0.0030    0.0000   0.0030     0.0060
Process = E subtracted from:

Process    Lower      Center     Upper
C        –0.003067  –0.001635  –0.000202
B        –0.004456  –0.002977  –0.001498
D        –0.005659  –0.004265  –0.002870
Process  ---------+---------+---------+---------+
3            (----*---)
4          (----*----)
5   (----*---)
      ---------+---------+---------+---------+
          –0.0030   0.0000    0.0030     0.0060
Process = C subtracted from:

Process    Lower      Center     Upper
B        –0.002857  –0.001343   0.000172
D        –0.004062  –0.002630  –0.001197
Process  ---------+---------+---------+---------+
B             (-----*----)
D          (----*----)
      ---------+---------+---------+----------+
          –0.0030   0.0000    0.0030     0.0060
Process = B subtracted from:

Process    Lower      Center     Upper
D        –0.002766  –0.001287   0.000191

Process  ---------+---------+---------+---------+
D             (----*----)
      ---------+---------+---------+---------+
          –0.0030    0.0000   0.0030     0.0060
```

Table 14—Least Significant Difference Test Summary.

Identification	Material	Form	Pre-Machining Heat Treatment	Mean (inches)	LSD Results			
A	AMS6265	Barstock	Normalized	–0.0024	*			
E	AMS6265	Barstock	Normalized + Harden at 1,550°F	–0.0025	*	*		
C	AMS6265	Forging	Normalized	–0.0041	<	*	*	
B	AMS6265	Barstock	Normalized + Harden at 1,725°F	–0.0054	<	<	*	*
D	AMS6260	Forging	Normalized + Harden at 1,725°F	–0.0067	<	<	<	*

* No significant difference
< Significantly less (greater distortion)

Appendices

Appendix A—Pre-Carburization Measurements.

	OD	Gap Spacing	ID
A1	1.491777	0.150892	0.899649
A2	1.491833	0.151428	0.900125
A3	1.491889	0.150585	0.899613
A4	1.491864	0.150973	0.899684
A5	1.491463	0.150015	0.899672
A6	1.491518	0.150853	0.899942
A7	1.491897	0.150621	0.899719
A8	1.491825	0.150812	0.899795
A9	1.491830	0.150944	0.899858
A10	1.491699	0.150987	0.900030
B1	1.492130	0.152432	0.900146
B2	1.492317	0.153077	0.900630
B3	1.492522	0.152497	0.900089
B4	1.492463	0.152678	0.900317
B5	1.491625	0.151338	0.899684
B6	1.492083	0.152111	0.900149
B7	1.492541	0.152803	0.899924
B8	1.492419	0.152584	0.900315
B9	1.492507	0.152580	0.900418
B10	1.492581	0.153003	0.900233
C1	1.491860	0.150922	0.899908
C2	1.491729	0.150592	0.899712
C3	1.491832	0.151115	0.900064
C4	1.491791	0.150683	0.899635
C5	1.491955	0.150670	0.899736
C6	1.491934	0.151392	0.899899
C7	1.491609	0.150840	0.899937
C8	1.491915	0.151113	0.900109
C9	1.491870	0.150559	0.899998
C10	Lost	Lost	Lost
D1	1.492250	0.151756	0.900008
D2	1.491899	0.151808	0.900183
D3	1.492145	0.151759	0.899833
D4	1.492065	0.152528	0.900248
D5	1.492137	0.152459	0.900129
D6	1.492179	0.152392	0.900245
D7	1.492041	0.151956	0.899926
D8	1.491958	0.151321	0.899859
D9	1.492036	0.151865	0.899980
D10	1.492078	0.151759	0.900184
E1	1.492131	0.151698	0.900366
E2	1.491914	0.151144	0.900140
E3	1.492083	0.151885	0.900468
E4	1.492361	0.152086	0.900438
E5	1.492284	0.151717	0.900376
E7	1.492164	0.151831	0.900428
E8	1.492032	0.151081	0.900134
E9	1.492078	0.151536	0.900413
E10	1.492299	0.151610	0.900472

Appendix B—Post-Carburization Measurements.

	OD	Gap Spacing	ID
A1	1.491036	0.149513	0.897343
A2	1.491033	0.149186	0.897657
A3	1.491074	0.149532	0.897460
A4	1.490823	0.149060	0.897494
A5	1.490611	0.149263	0.897529
A6	1.490611	0.149263	0.897529
A7	1.491253	0.150098	0.897605
A8	1.490949	0.149235	0.897345
A9	1.491172	0.150590	0.897772
A10	1.491054	0.150287	0.898095
B1	1.491714	0.152937	0.898456
B10	1.492180	0.154464	0.898883
B2	1.492036	0.155081	0.899100
B3	1.492176	0.154322	0.898438
B4	1.492103	0.154088	0.898413
B7	1.492114	0.154273	0.898710
B8	1.492174	0.154173	0.898928
B9	1.492286	0.155087	0.899138
B5	LOST	LOST	LOST
B6*	LOST	LOST	LOST
C1	1.491083	0.150262	0.897598
C2	1.491028	0.150367	0.897641
C3	1.491203	0.151182	0.898020
C4	1.490913	0.150017	0.897155
C5	1.491221	0.150286	0.897484
C6	1.490911	0.150548	0.897335
C7	1.490769	0.149977	0.897728
C8	1.491139	0.150862	0.897897
C9	1.491030	0.150444	0.897760
C10	n/a	n/a	n/a
D1	1.491950	0.152889	0.898381
D2	1.492083	0.153695	0.899254
D3	1.492136	0.150858	0.898572
D4	1.491993	0.153699	0.898730
D5	1.491990	0.154248	0.899122
D6	1.491921	0.153672	0.898613
D7	1.491956	0.153817	0.898573
D8	1.492084	0.153777	0.898988
D9	1.492042	0.152932	0.898640
D10	1.491930	0.153221	0.898834
E1	1.491661	0.150680	0.898204
E2	1.491171	0.148791	0.897786
E3	1.491507	0.150825	0.898149
E4	1.491724	0.150663	0.898007
E5	1.491690	0.151033	0.898181
E6	1.491878	0.151272	0.898550
E7	1.491368	0.150030	0.898024
E8	1.491368	0.149373	0.897778
E9	1.491636	0.150844	0.898181
E10	1.491526	0.150382	0.898124

Appendix C—Post-Hardening Measurements.

	OD	Gap Spacing	ID
A1	1.490619	0.153859	0.896438
A2	1.490324	0.150953	0.896028
A3	1.490521	0.153558	0.896269
A4	1.490384	0.149559	0.895761
A5	1.490182	0.152694	0.896224
A6	1.490096	0.152069	0.895832
A7	1.490696	0.154222	0.896680
A8	1.491107	0.155014	0.897004
A9	1.491320	0.154763	0.897174
A10	1.490682	0.154885	0.896899
B1	1.491049	0.155546	0.897306
B2	1.491620	0.160287	0.898406
B7	1.491654	0.156456	0.897311
B8	1.491752	0.157525	0.897314
B3	1.491890	0.158768	0.897481
B9	1.492070	0.157517	0.897928
B10	1.492194	0.158739	0.898371
B4	1.492214	0.160193	0.898008
B5	LOST	LOST	LOST
B6*	LOST	LOST	LOST
C1	1.491160	0.155660	0.897044
C2	1.491215	0.155423	0.897330
C3	1.491222	0.154394	0.897220
C4	1.490598	0.152489	0.896345
C5	1.491542	0.155456	0.897286
C6	1.491036	0.155915	0.897238
C7	1.491051	0.154720	0.897478
C8	1.491340	0.155252	0.897652
C9	1.491132	0.155293	0.897370
C10	LOST	LOST	LOST
D1	1.491620	0.158277	0.897585
D2	1.491678	0.158458	0.898110
D3	1.491564	0.157367	0.897579
D4	1.491434	0.156716	0.897350
D5	1.491647	0.158048	0.898135
D6	1.491498	0.159406	0.897923
D7	1.491640	0.160681	0.897562
D8	1.491546	0.158859	0.898226
D9	1.492222	0.159044	0.898479
D10	1.492237	0.159842	0.898467
E1	1.491506	0.156774	0.897493
E2	1.491710	0.155209	0.897627
E3	1.491097	0.156209	0.897153
E4	1.491192	0.152073	0.896542
E5	1.491046	0.152790	0.896751
E6	1.491338	0.154177	0.897434
E7	1.491418	0.154764	0.897454
E8	1.490914	0.152042	0.896596
E9	1.491246	0.153723	0.896996
E10	1.491191	0.152753	0.897002

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Appendix D—Sample Zeiss CMM Report (continued on p.44).

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                         MEASURING RECORD ZEISS  UMESS

Greg Blake Rounds                                              CNC RUN
=================
DRAWING NUMBER        | ORDER NUMBER        | SUPPLIER/CUSTOMER | OPERATION
N/A                   |N/A                  |Rolls Royce        |true position-form

OPERATOR              DATE          PART NUMBER
ADMIN                 06/20/03      a1

==============================================================================
 ADR|REC | TASK    | IDF |SY| ACTUAL    | NOMINAL   | U.TOL | L.TOL | DEV   | EXC
------------------------------------------------------------------------------
  13   12 *COORD. SYSTEM AS FOR  ADR.   12

##:OUTSIDE DIAMETER
  14  11! CIRCLEE      X    0.000000
                       Y   -0.000000
                       D    1.490619
                       S     .000050      FORM  .000241

DISTANCE OF SLOT OPENING AT MID-DEPTH
  17   15 DIST 16      X    0.153859

LOCATION AND SIZE OF CENTER BORE TO OD AND SLOT
##:INSIDE DIAMETER
Filter: DIN ISO EN 11562 (Gauss) Threshold wavelength =     25.00000
  18      CIRCLEI      X   -0.000583
                       Y    0.200309
                       D    0.896438
     211P S/MIN/MAX          .000054      (178)-.000074     (1;  000112


  4 hour 54 min 52.93sec

STATS STORED
=============================================
                                CNC - END
                              ===========
```

Appendix D (continued)