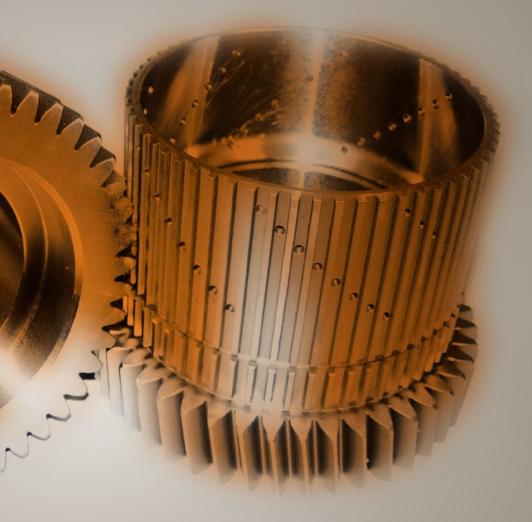
Improvements in Dimensional Control of Heat Treated Gears

The following study involves applying low pressure vacuum carburizing technology utilizing either oil or high pressure gas quenching in order to eliminate distortion.



By Frederick J. Otto and Daniel H. Herring



Figure 1: SAE 8620 Test Gears

The goals and objectives of this investigation focused on highly distortion-prone gearing (Fig. 1) to determine if dimensional improvements could be realized by applying low pressure vacuum carburizing technology utilizing either oil or high pressure gas quenching. The gears in question are traditionally atmosphere carburized and plug quenched.

Test Plan

Full production loads (Fig. 2) were run using two different carburizing methods (atmosphere, low pressure vacuum) in combination with free quenching in either oil at $165^{\circ}F(75^{\circ}C)$ or high pressure gas (nitrogen) at 11 bar.

Sampling Method

Gears were taken from multiple locations throughout each load for analysis (Table 1). Parts for metallurgical evaluation were selected from the center of each load. Multiple areas on each part were then analyzed for microstructure, case depth, and hard-



Figure 2: Typical Furnace Test Load (850 Pound Gross Load)



Figure 3: Clutch Gear, Test Gear Type "A"



Figure 4: 4" Clutch Hub, Test Gear Type "B"



Figure 5: 6" Clutch Hub, Test Gear Type "C"

GEAR TYPE	TEST LOCATION(S)	TEST AREA	HEAT TREAT Method [1]	CONDITION [1] (For Dimensional Testing)	
A (Fig. 3)	S = Spline T = Tooth	l = mid-point II = root III = tip	1 = LPC + HPGQ 2 = LPC + 0Q 3 = AC + 0Q	BHT Aht	
B (Fig. 4)	S = Spline	l = mid-point II = root III = tip	1 = LPC + HPGQ 2 = LPC + OQ 3 = AC + OQ	BHT Aht	D - 60000 - 600000 - 60000 - 600000
C (Fig. 5)	S = Spline	I = mid-point II = root III = tip	1 = LPC + HPGQ 2 = LPC + OQ 3 = AC + OQ	BHT Aht	IIGHT FLAMC 100320 jm* IIGHL INGK VARIATION 00320 jm* INDRF FICH VARIATION 00320 jm INDRF FICH VARIATION 000320 jm TOLFANGUE 000320 jm MORST FICH VARIATION 000320 jm NORDE ITEETH 21 AND 22 00042 jm MORST SPECIME VARIATION 000320 jm ANALYZED RUNUT 000320 jm ANALVED RUNUT 00332 jm AGMA CLASS SPECIFIED 010, CLASS ADHEVED 011 MARNING PITCH LINE VARIATION EXCEEDS AGMA RUNUT TOLERANCE

Table 1: Test Sample Matrix. Notes: 1) Abbreviations used: low pressure carburizing (LPC), high pressure gas quenching (HPGQ), atmo-sphere carburizing (AC) and oil quench (OQ); before heat treatment (BHT); and after heat treatment (AHT); 2) Existing heat treatment method is atmosphere carburizing (AC) and plug quenching.

Figure 6: Sample C, Before HT

ness (surface, profile, core). Dimensional checks (out of round, gear tooth profiles) were conducted on the gears before and after heat treatment. Although only a portion of the complete test program could be

presented here, the results are representative of the entire study.

Process Parameters

Carburizing was performed at 1760°F

(960°C) for 3.34 hours followed by either oil quenching (variable agitator speed) or high pressure gas quenching. Targeted surface carbon content was 0.72 percent C (vacuum) and 0.80-0.90 percent C

	Heat Trea	t Method 1	Heat Treat	Heat Treat Method 2		at Method 3
	50HRC	>58HRC	50HRC	>58HRC	50HRC	>58HRC
	inches	inches	inches	inches	inches	inches
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
A						
Gear Tooth	0.046	0.034	0.047	0.036	0.051	0.032
(mid-radius)	(1.17)	(0.86)	(1.19)	(0.91)	(1.30)	(0.81)
Gear Tooth	0.042	0.032	0.044	0.033	0.045	0.030
(root)	(1.07)	(0.81)	(1.12)	(0.84)	(1.14)	(0.76)
Spline	0.055	0.044	0.056	0.047	0.058	0.039
(mid-point)	(1.40)	(1.12)	(1.42)	(1.19)	(1.47)	(0.99)
Spline	0.051	0.040	0.054	0.043	0.052	0.038
(root)	(1.30)	(1.02)	(1.37)	(1.09)	(1.32)	(0.97)
В						
Spline	0.054	0.042	0.056	0.045	0.061	0.038
(mid-point)	(1.37)	(1.07)	(1.42)	(1.14)	(1.55)	(0.97)
Spline	0.050	0.040	0.053	0.042	0.060	0.035
(root)	(1.27)	(1.02)	(1.35)	(1.07)	(1.52)	(0.89)
С						
Spline	0.054	0.042	0.057	0.048	0.061	0.038
(mid-point)	(1.37)	(1.07)	(1.45)	(1.22)	(1.55)	(0.97)
Spline	0.051	0.041	0.054	0.044	0.060	0.036
(root)	(1.30)	(1.04)	(1.37)	(1.12)	(1.52)	(0.91)

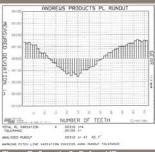


Figure 7: Sample C, Before HT

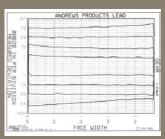


Figure 8: Sample C, Before HT

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Table 2: Effective Case Depth (50 HRC) and Depth of High Hardness (> 58 HRC)

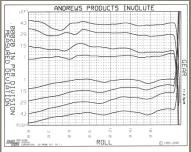


Figure 10: Sample C, After HT (LPC + HPGQ)

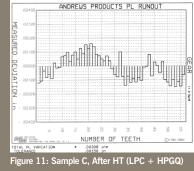




Figure 12: Sample C, After HT (LPC + HPGQ)

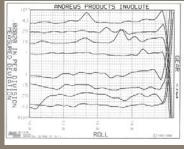


Figure 13: Sample C, After HT (LPC + HPGQ)

Figure 9: Sample C, Before HT

Depth Heat Treat Method 2 Gear Type Heat Treat Method 2 Gear Gear Heat Treat Treat Heat Treat Method 2 Gear Gear Heat Treat Gear Heat Treat Method 2 Gear Heat Treat Method 2 Gear Heat Treat Method 2 Gear	T		·	· · · · ·			
Gear Type A (mid-point) Gear Type B (mid-point) Gear Type B (mid-point) Gear Type C (mid-point) Method C (mid-point) Method 2 Gear Type A (root) Method 2 Gear Type B (root) Method 2 Gear Type C (root) 0.005 64 65 65 65 65 64 0.010 64 65 64 65 64 64 0.015 64 65 64 64 64 64 0.020 63 64 63 63 63 63 63 0.025 63 63 62 61 61 61 61 0.030 62 62 61 61 61 61 61 0.035 60 61 60 60 60 60 60 60 60 0.040 59 60 60 59 58 59 51 53 54 0.055 51 50 50 49 50 49 0.050 48 <td>Depth</td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td>	Depth						
A B C 2 2 2 Gear Type A (root) Gear Type A (root) Gear Type B (root) Gear Type C (root) 0.005 64 65 65 65 65 64 64 0.010 64 65 64 65 64 64 64 0.015 64 65 64 64 64 64 0.025 63 64 63 63 63 63 63 0.025 63 63 62 62 62 62 62 62 62 62 62 62 62 62 62 62 62 62 62 62 62 63							
(mid-point) (mid-point) (mid-point) (mid-point) Gear Type A (root) Gear Type B (root) Gear Type C (root) 0.005 64 65 65 65 65 64 64 0.010 64 65 64 65 64 64 64 0.015 64 65 64 65 64 64 64 0.020 63 64 63		Gear Type	Gear Type	Gear Type	Method	Method	Method
Normalized Type A (root) Type B (root) Type C (root) 0.005 64 65 65 65 65 64 0.010 64 65 64 65 64 64 64 0.025 63 64 63 63 63 63 63 0.015 64 65 64 64 64 64 0.020 63 64 63 63 63 63 0.025 63 63 62 62 62 62 0.030 62 62 61 61 61 61 0.035 60 61 60 60 60 60 0.040 59 60 60 59 58 59 1.011		Α	В	С	2	2	2
0.005 64 65 65 65 65 64 64 0.010 64 65 64 65 64 65 64 63 64 <t< td=""><td></td><td>(mid-point)</td><td>(mid-point)</td><td>(mid-point)</td><td>Gear</td><td>Gear</td><td>Gear</td></t<>		(mid-point)	(mid-point)	(mid-point)	Gear	Gear	Gear
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$					Type A	Туре В	Туре С
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$					(root)	(root)	(root)
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$							
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	0.005	64	65	65	65	65	64
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	(0.13)						
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	0.010	64	65	64	65	64	64
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	(0.25)						
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	0.015	64	65	64	64	64	64
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	(0.38)						
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	0.020	63	64	63	63	63	63
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	(0.51)						
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	0.025	63	63	62	62	62	62
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	(0.64)						
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	0.030	62	62	61	61	61	61
(0.89) 0 0 0 0 0 0 0 0 0 59 58 59 10	(0.76)						
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	0.035	60	61	60	60	60	60
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	(0.89)						
0.045 58 58 58 58 54 56 58 (1.14) -		59	60	60	59	58	59
(1.14)	(1.01)						
0.050 54 54 55 51 53 54 (1.27) -	0.045	58	58	58	54	56	58
(1.27)	(1.14)						
0.055 51 50 50 49 50 49 (1.40)	0.050	54	54	55	51	53	54
(1.40) 0.060 48 47 49 46 47 46 (1.52)	(1.27)						
0.060 48 47 49 46 47 46 (1.52)	0.055	51	50	50	49	50	49
0.060 48 47 49 46 47 46 (1.52)	(1.40)						
		48	47	49	46	47	46
Core 38 37 38.5 37 36 37	(1.52)						
Core 38 37 38.5 37 36 37	-						
	Core	38	37	38.5	37	36	37

Table 5: Hardness Profile Gear Type B, Test Location: Spline

Depth	Heat	Heat	Heat	Heat	Heat	Heat
inches	Treat	Treat	Treat	Treat	Treat	Treat
(mm)	Method	Method	Method	Method	Method	Method
(11111)	1	1	2	2	3	3
	(mid-	(root)	z (mid-	(root)	s (mid-	-
		(1001)	-	(1001)		(root)
	tooth)		radius)		tooth)	
0.005	64	63	65	64	63	63
(0.13)	04	03	05	04	03	03
0.010	64	62	64	63	63	63
	04	02	64	03	63	03
(0.25)	64	61	64		60	
0.015	64	61	64	62	62	62
(0.38)		~~~	64		~~~	
0.020	63	60	64	61	62	61
(0.51)						
0.025	62	59	62	60	61	60
(0.64)						
0.030	59	58	61	59	58	58
(0.76)						
0.035	57	54	59	54	57	56
(0.89)						
0.040	54	51	55	52	56	53
(1.01)						
0.045	50	47	52	50	53	50
(1.14)						
0.050	48	45	49	46	50	47
(1.27)						
0.055	39	41	44	43	48	43
(1.40)						
0.060	38	38	40	39	44	40
(1.52)						
Core	30	29	36	35	36	35

Table 3: Hardness Profile Gear Type A, Test Location: Gear Tooth

Method 1 Gear Type A (mid-point) Method 1 Gear Type B (mid-point) Method 1 Gear Type C (mid-point) Treat Method 1 Gear Type C (mid-point) Treat Method 1 Gear Type C (mid-point) Treat Method 1 Gear Type C (mid-point) Treat Method 1 Gear Type C (root) Treat Method 1 Gear Type Type A (root) Treat Method 1 Gear Type C (root) Treat Method 1 Gear Type C (root) Treat Method 1 Gear Type C (root) Treat Method 1 Gear Type Type C (root) 0.005 65 65 65 65 64 64 64 64 64 64 64 64 64 64 63 64 64 64 63 64 64 63 64 64 63 60 60 60 60 60 60 60 60 60 60 60 60 60 60 61 60 58 59 56 58 58 51 53 50 40 51 0.045 50 47 49 46 43 47 44 39 44 0.055 50 47 49 44<	Depth	Heat Treat	Heat Treat	Heat Treat	Heat	Heat	Heat
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$							
A B C 1 1 1 Gear Type A (root) Gear Type C (root) Gear Type (root) Gear Type (root) Gear		Gear Type		Gear Type			Method
Image: Constraint of the second sec				••	1	1	1
Image: Constraint of the second sec		(mid-point)	(mid-point)	(mid-point)	Gear	Gear	Gear
0.005 65 65 65 65 63 64 0.010 65 64 65 65 64 64 0.015 65 65 64 63 64 64 0.015 65 64 64 63 64 63 0.020 65 64 64 63 61 63 0.025 64 63 64 63 60 60 0.025 64 63 64 63 60 60 0.030 63 62 62 61 59 60 0.035 61 60 61 60 58 59 0.040 60 59 59 58 56 58 (1.01) 0.045 57 56 56 54 48 54 0.050 54 51 53 50 40 51 0.055 50 47		-	-	• •	Type A	Type B	Type C
					(root)	(root)	(root)
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	0.005	65	65	65	65	63	64
	(0.13)						
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	0.010	65	64	65	65	64	64
	(0.25)						
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	0.015	65	65	64	63	64	64
	(0.38)						
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	0.020	65	64	64	63	61	63
	(0.51)						
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$		64	63	64	63	60	60
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $							
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$		63	62	62	61	59	60
(0.89)							
0.040 60 59 59 58 56 58 (1.01) -		61	60	61	60	58	59
(1.01)							
0.045 57 56 56 54 48 54 (1.14) -		60	59	59	58	56	58
(1.14)							
0.050 54 51 53 50 40 51 (1.27)		57	56	56	54	48	54
(1.27)		+					
0.055 50 47 49 46 43 47 (1.40)		54	51	53	50	40	51
(1.40)		+					
0.060 46 43 45 44 39 44 (1.52)		50	47	49	46	43	47
(1.52)							
		46	43	45	44	39	44
Core 34 34 35 33 32 32	(1.52)						
Core 34 34 35 33 32 32							
	Core	34	34	35	33	32	32

Table 4: Hardness Profile Gear Type A, Test Location: Spline

Depth	Heat Treat	Heat Treat	Heat Treat	Heat	Heat	Heat
	Method 3	Method 3	Method 3	Treat	Treat	Treat
	Gear Type	Gear Type	Gear Type	Method	Method	Method
	Α	В	C	3	3	3
	(mid-point)	(mid-point)	(mid-point)	Gear	Gear	Gear
				Type A	Туре В	Туре С
				(root)	(root)	(root)
0.005	62	62	64	63	62	63
(0.13)						
0.010	62	63	65	63	63	64
(0.25)						
0.015	63	64	64	62	64	64
(0.38)						
0.020	63	64	63	61	62	62
(0.51)						
0.025	63	63	63	63	61	61
(0.64)						
0.030	61	61	62	61	59	60
(0.76)						
0.035	60	60	60	59	58	58
(0.89)						
0.040	57	57	57	57	55	57
(1.01)						
0.045	56	55	56	54	53	55
(1.14)						
0.050	55	54	54	50	52	52
(1.27)						
0.055	53	52	52	49	51	51
(1.40)						= -
0.060	49	50	50	46	50	50
(1.52)						
Core	36	35	36	35	36	37
COL	50	55	50	55	50	57

(atmosphere). Gas quenching utilized four changes in speed and pressure made through the critical transformation range of the material while the oil quench utilized two changes in speed (70 and 40 percent). Tempering was performed at 300°F (150°C) for two hours at temperature.

Test Results

Surface hardness of all low pressure vacuum carburized gears was in the 64-65 HRC range. Atmosphere carburized gears exhibited a slightly lower surface hardness, in the 62-63 HRC range.

The depth of high hardness (> 58 HRC) was 0.002"-0.005" (0.05-0.13 mm) deeper for the low pressure vacuum carburized gears than for the atmosphere carburized gears (Table 2). The root-to-pitch line case depth ratio was 92-94 percent (vacuum carburizing) versus 63 percent (atmosphere carburizing). See selected data found in Tables 2-6.

Distortion

Dimensional variation was determined by measuring both out of round (Table 7) and by coordinate measuring machine (CMM) measurement of the gear tooth profiles (Figs. 6-13). With respect to the gear charts shown, the lead was measured across the

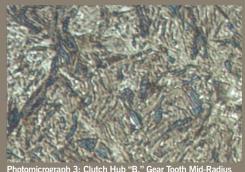
Table 6: Hardness Profile Gear Type C, Test Location: Spline



HPGQ) 1250X Nital



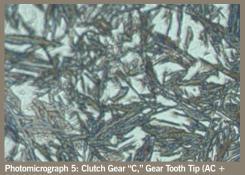
(LPC + HPGQ) 1250X Nital



(LPC + OQ) 1250X Nital



(AC + OQ) 1250X Nital



Q) 1250X Nital

Gear	Test Location	Heat Treat	Heat Treat	Heat Treat
Туре	S	Method 1	Method 2	Method 3
		(LPC+HPGQ)	(LPC+OQ)	(AC+OQ)
		inches (mm)	inches (mm)	inches (mm)
Α	top	0.0052 (0.1320)	0.0156 (0.3962)	0.0420 (1.0668)
	middle	0.0033 (0.0838)	0.0095 (0.2413)	0.0225 (0.5715)
	bottom	0.0017 (0.0431)	0.0062 (0.1574)	0.0162 (0.4115)
В	top	0.0044 (0.1117)	0.0139 (0.3530)	0.0344 (0.8737)
	middle	0.0031 (0.0787)	0.0091 (0.2311)	0.0203 (0.5156)
	bottom	0.0018 (0.0457)	0.0058 (0.1473)	0.0137 (0.3479)
С	top	0.0037 (0.0939)	0.0127 (0.3225)	0.0278 (0.7061)
	middle	0.0032 (0.0812)	0.0084 (0.2133)	0.0164 (0.4165)
	bottom	0.0016 (0.0406)	0.0042 (0.1066)	0.0119 (0.3022)

Table 7: Out of Round (Spline). Note: The existing heat treating method (atmosphere carburizing and plug quenching) results in out of round values typically in the range of 0.002"-0.003" (0.0508-0.0762 mm).

tooth or spline from side to side at the pitch diameter. This method checked for excessive taper. The involute measurement was taken on the tooth form (active profile), starting from the root diameter to the tip of the tooth. Indexing (index error) measured the tooth spacing from tooth to tooth around the gear. Gear or spline run-out measured variation of concentricity of the centerline (datum) of the gear.

Microstructure

Analysis of part microstructures from low pressure vacuum carburized gears (Photomicrographs 1-3) taken from all areas (tip, mid-radius, root) revealed a tempered martensite structure with small amounts of retained austenite. Atmosphere carburized gears (Photomicrographs 4-5) revealed the presence of large amounts of retained austenite (tip, mid-radius).

Conclusions

The following are the principle results of this investigation:

- Low pressure vacuum carburizing in combination with high pressure gas quenching produced consistent repeatability. This degree of predictable movement is capable of being compensated for in the manufacturing process.
- Low pressure vacuum carburizing in combination with high pressure gas quenching allowed for the replacement

of atmosphere carburizing and plug quenching on the gears investigated in this study.

- The depth of high hardness (> 58 HRC) was greatest in the low pressure vacuum carburized samples.
- The root-to-pitch line case depth ratio was superior in vacuum carburizing (approximately 93 percent, versus 63 percent).
- Atmosphere carburizing resulted in unacceptable levels of retained austenite.
- Gear charts indicated an average movement of 0.003" (0.08 mm). The involute form remained intact after low pressure vacuum carburizing and gas quenching as did the lead on the gear teeth and splines.

ABOUT THE AUTHORS:

Frederick J. Otto is president of Midwest Thermal-Vac [www.mtvac.com] and Daniel H. Herring—known as "The Heat Treat Doctor"—is president and founder of The Herring Group, Inc. [www.heat-treat-doctor.com].

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