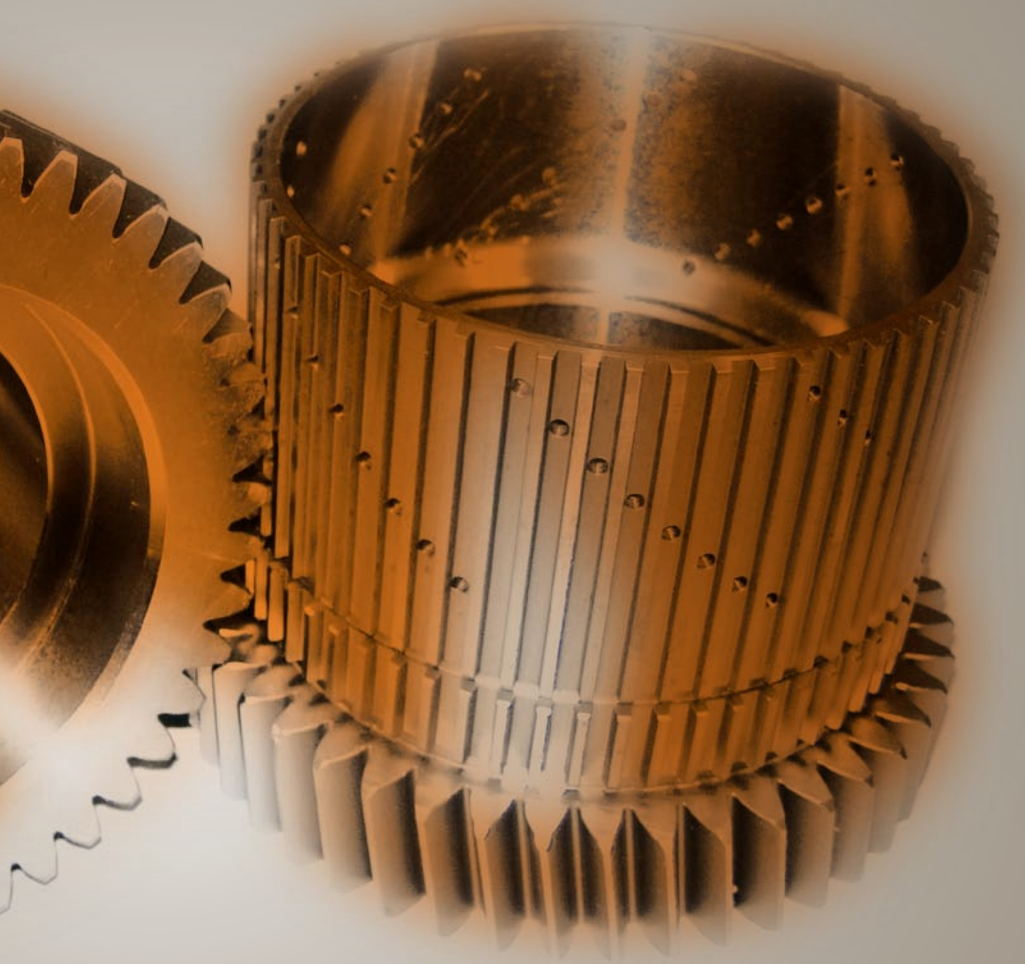
# Improvements in Dimensional Control of Heat Treated Gears

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°F (75°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<br>T = Tooth | I = mid-point<br>II = root<br>III = tip | 1 = LPC + HPGQ<br>2 = LPC + OQ<br>3 = AC + OQ | BHT<br>AHT |
| B (Fig. 4) | S = Spline | I = mid-point<br>II = root<br>III = tip | 1 = LPC + HPGQ<br>2 = LPC + OQ<br>3 = AC + OQ | BHT<br>AHT |
| C (Fig. 5) | S = Spline | I = mid-point<br>II = root<br>III = tip | 1 = LPC + HPGQ<br>2 = LPC + OQ<br>3 = AC + OQ | BHT<br>AHT |

Table 1: Test Sample Matrix. Notes: 1) Abbreviations used: low pressure carburizing (LPC), high pressure gas quenching (HPGQ), atmosphere 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.

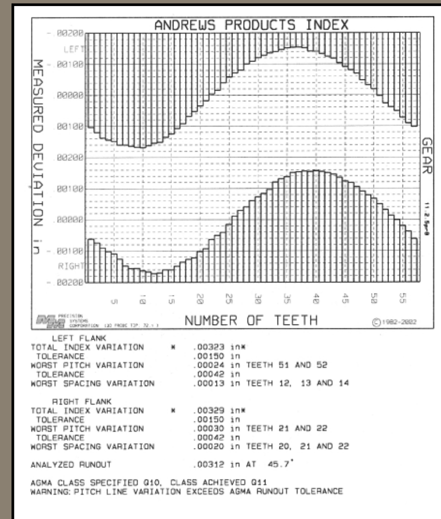



Figure 6: Sample C, Before HT

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

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

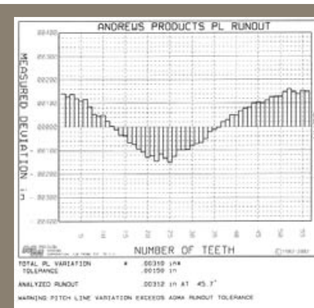



**Figure 7: Sample C, Before HT**

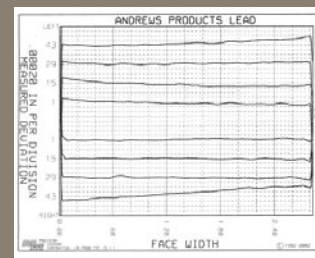



**Figure 8: Sample C, Before HT**

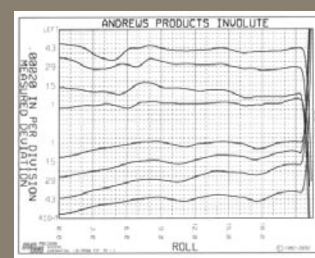



**Figure 9: Sample C, Before HT**

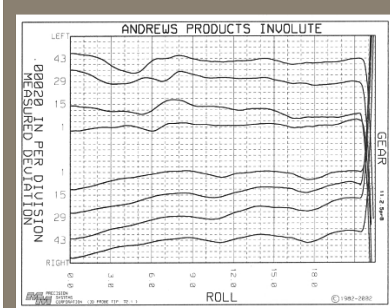



**Figure 10: Sample C, After HT (LPC + HPGQ)**

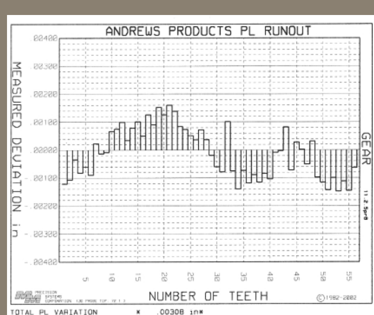



**Figure 11: Sample C, After HT (LPC + HPGQ)**

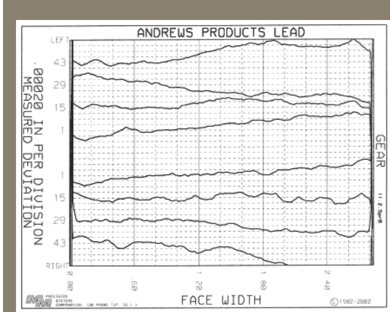



**Figure 12: Sample C, After HT (LPC + HPGQ)**

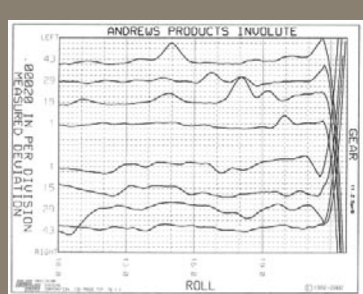



**Figure 13: Sample C, After HT (LPC + HPGQ)**

| Depth | Heat Treat Method 2 Gear Type A (mid-point) | Heat Treat Method 2 Gear Type B (mid-point) | Heat Treat Method 2 Gear Type C (mid-point) | Heat Treat Method 2 Gear Type A (root) | Heat Treat Method 2 Gear Type B (root) | Heat Treat Method 2 Gear Type C (root) |
|---|---|---|---|---|---|---|
| | | | | | | |
| 0.005 (0.13) | 64 | 65 | 65 | 65 | 65 | 64 |
| 0.010 (0.25) | 64 | 65 | 64 | 65 | 64 | 64 |
| 0.015 (0.38) | 64 | 65 | 64 | 64 | 64 | 64 |
| 0.020 (0.51) | 63 | 64 | 63 | 63 | 63 | 63 |
| 0.025 (0.64) | 63 | 63 | 62 | 62 | 62 | 62 |
| 0.030 (0.76) | 62 | 62 | 61 | 61 | 61 | 61 |
| 0.035 (0.89) | 60 | 61 | 60 | 60 | 60 | 60 |
| 0.040 (1.01) | 59 | 60 | 60 | 59 | 58 | 59 |
| 0.045 (1.14) | 58 | 58 | 58 | 54 | 56 | 58 |
| 0.050 (1.27) | 54 | 54 | 55 | 51 | 53 | 54 |
| 0.055 (1.40) | 51 | 50 | 50 | 49 | 50 | 49 |
| 0.060 (1.52) | 48 | 47 | 49 | 46 | 47 | 46 |
| | | | | | | |
| Core | 38 | 37 | 38.5 | 37 | 36 | 37 |

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

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

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

| Depth | Heat Treat Method 1 Gear Type A (mid-point) | Heat Treat Method 1 Gear Type B (mid-point) | Heat Treat Method 1 Gear Type C (mid-point) | Heat Treat Method 1 Gear Type A (root) | Heat Treat Method 1 Gear Type B (root) | Heat Treat Method 1 Gear Type C (root) |
|---|---|---|---|---|---|---|
| | | | | | | |
| 0.005 (0.13) | 65 | 65 | 65 | 65 | 63 | 64 |
| 0.010 (0.25) | 65 | 64 | 65 | 65 | 64 | 64 |
| 0.015 (0.38) | 65 | 65 | 64 | 63 | 64 | 64 |
| 0.020 (0.51) | 65 | 64 | 64 | 63 | 61 | 63 |
| 0.025 (0.64) | 64 | 63 | 64 | 63 | 60 | 60 |
| 0.030 (0.76) | 63 | 62 | 62 | 61 | 59 | 60 |
| 0.035 (0.89) | 61 | 60 | 61 | 60 | 58 | 59 |
| 0.040 (1.01) | 60 | 59 | 59 | 58 | 56 | 58 |
| 0.045 (1.14) | 57 | 56 | 56 | 54 | 48 | 54 |
| 0.050 (1.27) | 54 | 51 | 53 | 50 | 40 | 51 |
| 0.055 (1.40) | 50 | 47 | 49 | 46 | 43 | 47 |
| 0.060 (1.52) | 46 | 43 | 45 | 44 | 39 | 44 |
| | | | | | | |
| Core | 34 | 34 | 35 | 33 | 32 | 32 |

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

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

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

(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.

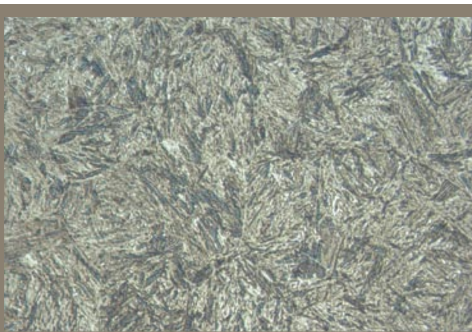
## Test Results

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.

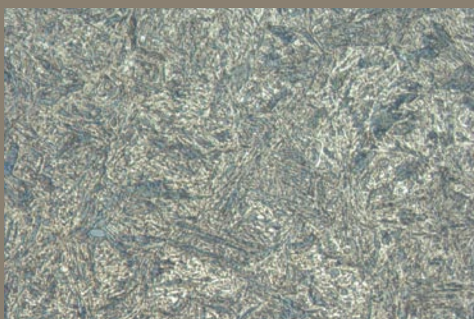
The depth of high hardness (> 58 HRC) was 0.002”-0.005” (0.05-0.13 mm) deeper for the low pressure vacuum carburized gears than for the atmosphere carburized gears (Table 2). The root-to-pitch line case depth ratio was 92-94 percent (vacuum carburizing) versus 63 percent (atmosphere carburizing). See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

## Distortion

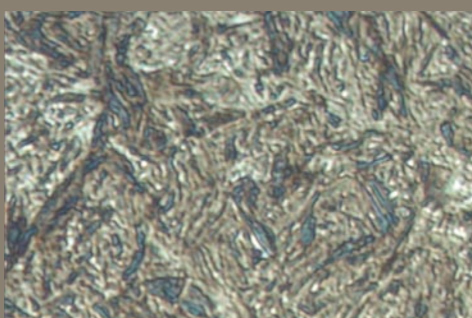
Dimensional variation was determined by measuring both out of round (Table 7) and by coordinate measuring machine (CMM) measurement of the gear tooth profiles (Figs. 6-13). With respect to the gear charts shown, the lead was measured across the



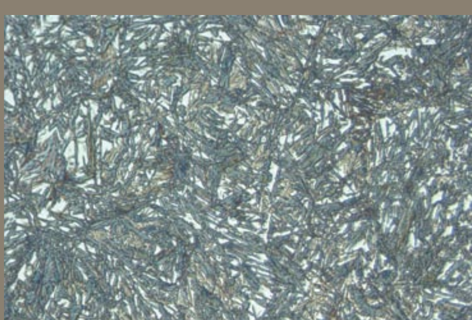
Photomicrograph 1: Clutch Gear "A," Spline Mid-Point (LPC + HPGQ) 1250X Nital



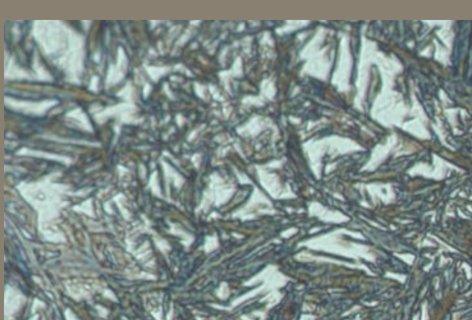
Photomicrograph 2: Clutch Gear "A," Gear Tooth Mid-Radius (LPC + HPGQ) 1250X Nital



Photomicrograph 3: Clutch Hub "B," Gear Tooth Mid-Radius (LPC + OQ) 1250X Nital



Photomicrograph 4: Clutch Gear "C," Gear Tooth Mid-Radius (AC + OQ) 1250X Nital



Photomicrograph 5: Clutch Gear "C," Gear Tooth Tip (AC + OQ) 1250X Nital

| Gear Type | Test Location S | Heat Treat Method 1 (LPC+HPGQ) inches (mm) | Heat Treat Method 2 (LPC+OQ) inches (mm) | Heat Treat Method 3 (AC+OQ) inches (mm) |
|---|---|---|---|---|
| | | | | |
| A | 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) |
| | | | | |
| B | 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) |
| | | | | |
| C | 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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