Atmosphere vs. Vacuum Carburizing

Gerald D. Lindell, Daniel H. Herring, David J. Breuer and Beth S. Matlock

Residual stress and microhardness data are used to compare atmosphere and vacuum carburizing of a low-alloy gear steel, and the effects of high-pressure gas quenching and post-heat treat grinding and shot peening are investigated.

Fig. 1 — These Twin Disc transmissions incorporate 14 to 16 large gears like the one shown above at right. The six-pitch helical gear is for one of the three 205 mm (8 in.) clutch pack assemblies in a TD-61-1175 transmission (right). The SAE 8620RH gear is carburized to 0.81 mm (0.032 in.) min. finished effective case depth at 60 to 64 HRC surface hardness. The TD-61-1175 transmission is used in airport crash-fire vehicles. It's rated at 400 kW (540 hp) at 2,300 max. rpm. The 2600 series transmission, above, is used in Versatile 1150 series tractors. It's rated at 520 kW (700 hp) at 2,200 max. rpm. Photos courtesy Twin Disc Inc.

In recent years, improvements in the reliability of the vacuum carburizing process have allowed its benefits to be realized in high-volume, critical component manufacturing operations. The result: parts with enhanced hardness and mechanical properties.

The purpose of the study described in this article was to investigate whether vacuum carburizing could be used to improve fatigue life. Fatigue is a major cause of gear failure, where the primary failure modes are gear tooth root bending and tooth pitting.

AISI 8620 Steel Studied

Twin Disc Inc. is a world-class supplier of heavy-duty transmissions and related equipment for off-road vehicles (Fig. 1).

Gears are an integral part of these assemblies, and they are carburized to produce a hard, fatigue-resistant case supported by a lower strength, ductile core.

The manufacturing of high-quality transmission gearing involves careful consideration of a number of critical factors, including component design, material, heat treatment, and the influence of subsequent manufacturing operations such as shot peening and grinding.

The methods used to compare the vacuum and atmosphere carburizing processes in this study were X-ray diffraction and microhardness testing.

Coupons of AISI 8620 low-alloy steel were heat treated using the different carburizing methods and subjected to identical post-heat treat grinding and shot peening operations.

X-ray diffraction was selected because it can be used to measure residual stresses. Residual stresses are additive with applied stress, which makes their level an important factor in fatigue-critical components such as gears. Residual compressive stresses are desirable because they oppose the applied, repetitive, and undesirable tensile stresses that cause fatigue failure. For gears, the areas of most concern are the flanks, which are subjected to contact loads that could cause pitting fatigue, and the roots, which experience tensile bending fatigue loads.

The greater the magnitude and depth of residual compressive stress, the greater the ability to improve fatigue properties. To enhance resistance to fatigue crack initiation, it is particularly important to have a higher compressive stress level at the outer surface. Also note that a deeper layer of compressive stress provides resistance to fatigue crack growth for a longer time than a shallower layer.

Carburizing process. Carburizing of a metal surface is a function of both the rate of carbon absorption into the steel and the diffusion of carbon away from the surface and into the interior of the part. Once a high concentration of carbon has developed at the surface, during what is commonly called the "boost stage," the process normally introduces a "diffuse stage," where solid-state diffusion occurs over time. This step results in a change in the carbon concentration gradient between the carbon-rich surface and the steel's interior. The result is a reduction of carbon concentration at the surface of the part accompanied by an increase in the depth of carbon absorption.

The carburization process also induces desirable residual compressive stresses through the case hardened layer. This stress state results from the delayed transformation and volume expansion of the carbon-enriched surface of the steel.

Atmosphere Carburizing

In atmosphere carburizing, parts are heated to austenitizing temperature in a "neutral" or "carrier" gas atmosphere that contains approximately 40% hydrogen (H_2), 40% nitrogen (N_2), and 20% carbon monoxide (CO). Small percentages of carbon dioxide (CO_2, up to 1.5%), water vapor (H_2O, up to 1%), and methane (CH_4, up to 0.5%), along with trace amounts of oxygen (O_2), also are present. The carburizing process also requires the addition of a hydrocarbon enriching gas, usually natural gas.

Of the 180 chemical equations that describe the reactions occurring during atmosphere carburizing, one of the most important is the water-gas reaction:

$$CO + H_2O = CO_2 + H_2 \qquad (1)$$

Control of the atmosphere carburizing process is done by looking at the CO/CO_2 and H_2O/H_2 ratios of this equation using instruments such as dew point analyzers, infrared analyzers, and oxygen (carbon) probes.

In atmospheres containing CO and H_2, carbon transfer is dominated by the CO adsorption (ad) and the oxygen desorption reactions:

$$CO \rightarrow CO_{ad} \rightarrow [C] + O_{ad} \qquad (2)$$

$$O_{ad} + H_2 \rightarrow H_2O \qquad (3)$$

These two reactions yield an alternate form of the water-gas reaction:

$$CO + H_2 = [C] + H_2O \qquad (4)$$

Thus, the transfer of carbon in atmospheres containing CO and H_2 is connected with a transfer of oxygen, giving rise to an oxidation effect in steel containing oxide-forming alloying elements such as silicon, chromium and manganese. This phenomenon is known as internal or intergranular oxidation of steel.

Figure 2 shows hardness profiles for an atmosphere-carburized and oil-quenched AISI 8620 steel gear.

Atmosphere carburizing to a depth of 0.36 mm (0.014 in.) produced a hardness of 58 HRC at both the gear tooth pitch line and root. From this depth, the hardness values quickly diverge. The effective case depth (at 50 HRC) is 0.76 mm (0.030 in.) in the root and 1.33 mm (0.0525 in.) at the pitch diameter. These values are typical of the vast majority of carburized gears currently in service.

For resistance to bending fatigue, it is desirable to achieve a deeper case in the root. This produces a deeper level of high-hardness, high-strength material with the benefit of residual compressive stress.

Vacuum Carburizing

Vacuum carburizing or low-pressure carburizing, by comparison, does not use a "carrier gas" atmosphere, but instead uses vacuum pumps to remove the atmosphere from the chamber before the process begins. For carburizing to take place in a vacuum furnace, all that's needed is a small, controlled addition of a hydrocarbon gas.

Unlike atmosphere carburizing, the breakdown of hydrocarbons in vacuum carburizing is via nonequilibrium reactions. This means that the carbon content at the surface of the steel is very rapidly raised to the saturation level of carbon in austenite. By repeating the boost and diffuse steps, any desired carbon profile and case depth can be achieved.

Today, vacuum carburizing is best performed using low-pressure techniques under 20 torr (25 mbar), and typically at tempera-

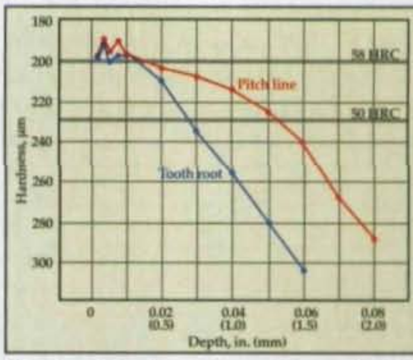

Fig. 2 — Microhardness profiles at pitch line and tooth root for an atmosphere-carburized and oil-quenched AISI 8620 gear. For resistance to bending fatigue, it is desirable to achieve a deeper case in the root.

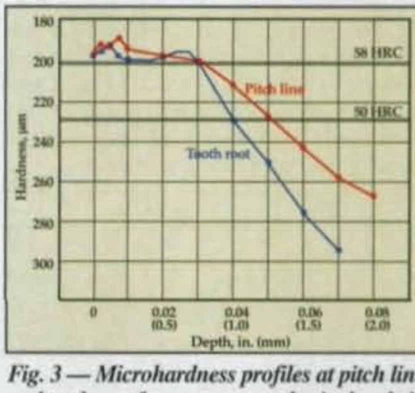

Fig. 3 — Microhardness profiles at pitch line and tooth root for a vacuum-carburized and oil-quenched AISI 8620 gear. The overall case depth of maximum hardness is deeper than that of the atmosphere-carburized part in Fig. 2.

Gerald D. Lindell

is corporate engineering metals specialist at Twin Disc Inc., located in Racine, WI. Twin Disc manufactures complete transmissions as well as power take-offs, clutches, couplings, torque converters and components for marine, off-highway and industrial applications.

Daniel H. Herring

is president of The Herring Group Inc., located in Elmhurst, IL. The Herring Group provides heat treating and metallurgical services, including education and training, consulting, product/process analysis and equipment diagnostics.

David J. Breuer

is regional director-technical sales, for Metal Improvement Co. Inc. of Milwaukee, WI. Metal Improvement, a subsidiary of the Curtiss-Wright Corp., has specialized in providing shot-peening services to industry since 1945. The company also has heat treating operations around the world.

Beth S. Matlock

is senior materials engineer at TEC—Technology for Energy Corp., located in Knoxville, TN. TEC designs and manufactures diagnostic instruments for the nuclear power industry, materials testing, aviation maintenance diagnostics and electric power measurement.

tures between 790 and 1,040°C (1,475 and 1,900°F). Hydrocarbon gases currently being used for vacuum carburizing are acetylene (C_2H_2), propane (C_3H_8), and, to a lesser degree, ethylene (C_2H_4). Methane (CH_4) is not used because it is nearly nonreactive at these low pressures, unless the temperature is at or above 1,040°C (1,900°F).

Carbon is delivered to the steel surface in vacuum carburizing via reactions such as these:

$$C_2H_2 \rightarrow 2C + H_2 \quad (5)$$

$$C_3H_8 \rightarrow CH_4 + C_2H_4 \rightarrow C + 2CH_4 \quad (6)$$

$$C_2H_4 \rightarrow C + CH_4 \quad (7)$$

In the past, propane has been the primary hydrocarbon gas used for vacuum carburizing; however, propane dissociation occurs before the gas comes in contact with the surface of the steel, thus producing free carbon or soot. This uncontrolled soot formation results in poor carbon transfer to the part and loss of up-time productivity due to the need for additional heat treat equipment maintenance.

Development work done in the past few years has demonstrated that acetylene is a good performing gas for vacuum carburizing. This is because the chemistry of acetylene (Eq. 5) is vastly different from that of propane or ethylene (Eq. 6 and 7). Dissociation of acetylene delivers two carbon atoms to the one produced by dissociation of either propane or ethylene and avoids formation of nonreactive methane.

Control of the vacuum carburizing process is on a time basis. Carbon transfer rates are a function of temperature, gas pressure, and gas flow rate. Simulation programs have been written to determine the boost and diffuse times of the cycle.

Figure 3 shows hardness profiles for a vacuum-carburized and oil-quenched AISI 8620 steel gear.

The overall case depth of maximum hardness for the vacuum carburized part is noticeably deeper than that of the atmosphere carburized part in Fig. 2. The vacuum carburized case depth of approximately 0.81 mm (0.032 in.) at 58 HRC is more than double that obtained with atmosphere carburizing, while the effective case depths (depth at 50 HRC) are similar. Also note the much greater consistency in root and pitch line hardnesses through a depth of 0.81 mm (0.032 in.) for vacuum carburizing vs. atmosphere carburizing (Fig. 3 vs. Fig. 2).

The hardness profiles shown in Fig. 4 are for an AISI 8620 steel gear that has been vacuum carburized and then high-pressure gas quenched in 20-bar nitrogen.

A comparison of Figures 3 and 4 shows that use of high-pressure gas quenching instead of oil quenching in vacuum carburizing results in a more uniform case depth between gear pitch line and root. The absence of a vapor layer in gas quenching results in a more uniform cooling rate along the gear tooth and root profile.

Test Procedure Outlined

The following procedure was used to properly evaluate the effect of different heat treatments and post-heat treatment processes on residual stress in coupons of AISI 8620 low-alloy gear steel.

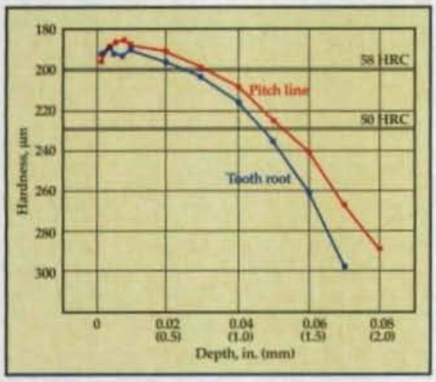

Fig. 4 — Microhardness profiles at pitch line and tooth root for a vacuum carburized and high-pressure gas quenched AISI 8620 steel gear. Use of gas quenching instead of oil quenching (Fig. 3) results in a more uniform case depth between pitch line and root.

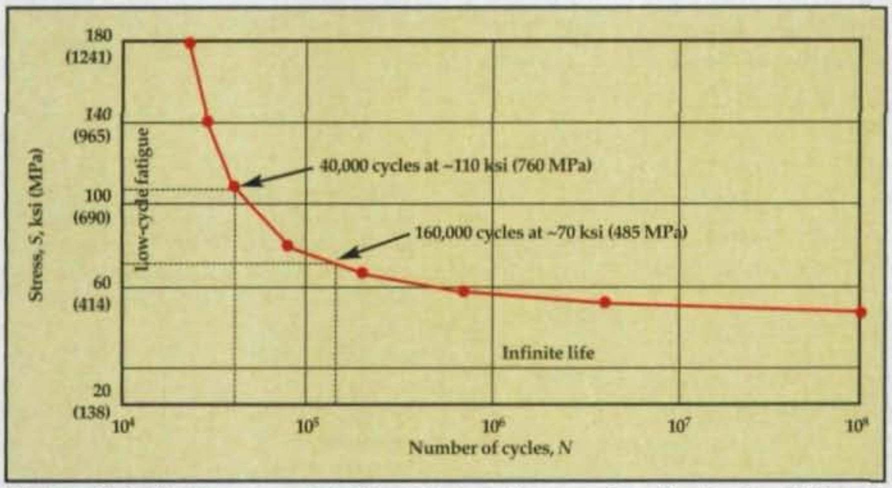

Fig. 5 — Typical S-N curve, or plot of (tensile) stress, S, vs. number of load cycles, N. The primary purpose of shot peening gears is to enhance their fatigue life by inducing a high residual compressive stress at the surface of the tooth roots. Shot peening is most effective for parts subject to high-cycle fatigue loading (>10^4 to 10^5 cycles).

Table 1 — Test coupon manufacturing processes

Coupon	ID	Process
1	EX2470	Vacuum carburize (VC)
2	EX2470-1	Vacuum carburize and shot peen (VC&SP)
3	EX2470-2	Atmosphere carburize (AC)
4	EX2470-3	Atmosphere carburize and shot peen (AC&SP)
5	EX2470-4	Vacuum carburize and dual shot peen (VC&DSP)

Table 2 — Test parameters for atmosphere and vacuum carburized coupons

Parameter	Atmosphere	Vacuum
Temperature, °C (°F)	940 (1,725)	940 (1,725)
Boost time, min	300	32
Diffusion time, min	120	314
Hardening temperature, °C (°F)	845 (1,550)	845 (1,550)
Quenching method	Oil at 60°C (140°F)	Nitrogen gas at 20 bar
Tempering temperature, °C (°F)	175 (350)	175 (350)
Tempering time, h	2	2

• Five coupons from the same heat lot of AISI 8620 were cut to size: 76 X 19 X 13 mm, ± 0.05 mm (3.00 X 0.75 X 0.505 in., ± 0.002 in.). The coupons were stamped, and a separate manufacturing process was defined for each (Table 1).

• Coupons were sent out for heat treatment—vacuum or atmosphere carburizing—according to the parameters in Table 2. The required surface hardness was 59 to 61 HRC. Vacuum carburized coupons were nitrogen gas quenched, while atmosphere carburized coupons were oil quenched.

• Heat treated coupons were ground to 12.7 mm ± 0.013 mm (0.5000 in. ± 0.0005 in.), removing no more than 0.15 mm (0.006 in.) from the nonstamped side where X-ray diffraction was to take place.

• Three of the five coupons were sent out for shot peening.

• All five coupons were sent out for X-ray diffraction on the nonstamped side.

Shot Peening's Benefits

The primary purpose of shot peening gears is to enhance their fatigue life by inducing a high residual compressive stress at the surface of the tooth roots. Shot peening is most effective for parts subject to high-cycle fatigue loading.

A basic explanation is provided by the graph in Fig. 5, a typical *S-N* curve. It plots (tensile) stress, *S*, vs. the number of load cycles, *N*. It is important to note that the vertical scale is linear, whereas the horizontal scale is logarithmic. This means that as tensile stress is reduced, fatigue life improves exponentially. A reduction of stress from 760 MPa (110 ksi) to 485 MPa (70 ksi) results in an improvement in fatigue life from 40,000 cycles to 160,000 cycles (400%). Additional reductions in tensile stress result in significantly more fatigue enhancement. At 415 MPa (60 ksi), for example, the anticipated fatigue life is approximately 400,000 cycles.

The residual compressive stresses produced by shot peening counteract applied tensile stresses. The compressive stresses are induced by impacts of small, spherical media (shot). The impact of each individual shot stretches the surface enough to yield it in tension. Because the surface cannot fully restore itself due to the mechanical yielding that has taken place, it is left in a permanent compressed state.

Shot peening results in a residual compressive stress at the surface—where most fatigue cracks initiate—that is approximately 55 to 60% of the material's ultimate tensile strength. For carburized gears, the surface compression is typically 1,170 to 1,725 MPa (170 to 250 ksi), which results in a significant improvement in fatigue properties.

Grinding Often Overlooked

The grinding process is applied to components so often and in so many forms (automatic, manual, with and without coolant) that it is often overlooked from a residual stress standpoint. However, its influence should not be discounted, especially when dealing with fatigue-critical parts.

During grinding, residual tensile stress may be created from generation of excessive, localized heat. The localized surface area being ground heats from friction and attempts to expand, but can't because it is surrounded by cooler, stronger metal. If the temperature generated from grinding is high enough, however, the metal yields in compression due to the resistance to its expansion and reduced mechanical properties at elevated temperature. Upon cooling, the yielded material attempts to contract. The surrounding material resists this contraction, thus creating residual tensile stress. Because heat is the major cause of residual tensile stress from grinding, the importance of coolant for controlling these stresses is paramount.

X-Ray Diffraction Measures Stresses

X-ray diffraction was used to measure the residual stresses at surface and subsurface locations. The technique measures strain by measuring changes in atomic distances. It is a direct, self-calibrating method that measures tensile, compressive, and neutral strains equally well. Strains are converted to stresses by multiplying by elastic constants appropriate for the alloy and atomic planes measured.

For this study, chromium Kα radiation was used to diffract the (211) planes at approximately 156° 2θ. The area measured was nominally 4 mm (0.16") in diameter. Since only a few atomic layers are measured, the technique is considered a surface analysis technique. The subsurface measurements

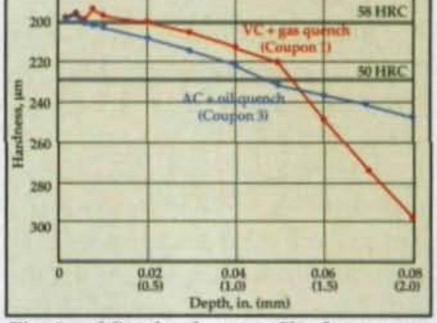

Fig. 6 — Microhardness profiles for vacuum carburized and gas quenched (Coupon 1) and atmosphere carburized and oil quenched (Coupon 3) AISI 8620 steel coupons. A major advantage of vacuum carburizing is a deeper case of high hardness.

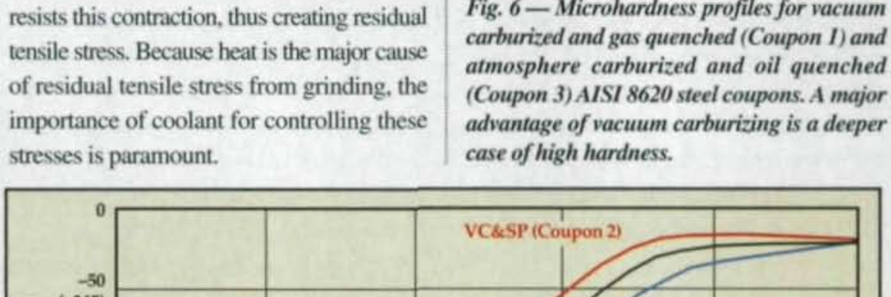

Fig. 7 — Residual stress distributions in the three carburized, ground, and shot peened coupons (Coupons 2, 4, and 5) of AISI 8620. Each boasts a solid layer of compression that implies excellent resistance to initiation and growth of fatigue cracks. Note that the residual stress curve for dual-peened Coupon 5 is ~0.025 to 0.05 mm (0.001 to 0.002 in.) deeper than those for the single-shot-peened coupons.

Table 3 — Comparison of atmosphere and vacuum carburizing results

Property	Atmosphere	Vacuum
Depth to 58 HRC, mm (in.)	0.20 (0.008)	0.58 (0.023)
Surface hardness before grinding, HRC	59	60
Surface hardness after removal of 0.1 mm (0.004 in.) stock by grinding, HRC	58	62

were made by electrochemically removing small amounts of material. These subsurface measurements were subsequently corrected for stress gradient and layer removal effects using standard analytical calculations.

Comparing the Processes

Hardness profiles for vacuum carburized (Coupon 1) and atmosphere carburized (Coupon 3) AISI 8620 steel coupons are compared in Fig. 6. A major advantage of vacuum carburizing over atmosphere carburizing is a deeper case of high hardness. Hardness values for the two carburizing processes are given in Table 3.

Effect of peening. Residual stress distributions in the three carburized, ground, and shot peened coupons—Coupons 2, 4, and 5—are plotted in Fig. 7.

From a fatigue standpoint, the solid layer of compression demonstrated for all three coupons implies excellent resistance to initiation and growth of fatigue cracks. The tensile stress required for a fatigue crack to develop must first overcome compressive stresses that are approximately 1,035 MPa (150 ksi) at the surface and approximately 1,515 MPa (220 ksi) at 0.05 mm (0.002 in.) below the surface. A tensile stress of 1,035 MPa (150 ksi) will produce a net stress of 0 MPa (0 ksi) at the surface when added to the residual compressive stress.

Coupons 2 and 4 were shot peened at an Almen intensity of 14 to 16. (Almen intensity is a measure of the energy of the shot stream.) The steel shot had a hardness of 55 to 62 HRC and a nominal diameter of 0.58 mm (0.023 in.).

The residual stress curves in Fig. 7 have shapes typical of shot peened material. All three have a similar maximum compressive stress of approximately 1,515 MPa (220 ksi). This value is approximately 55 to 60% of the steel's ultimate tensile strength at the surface. Because all three coupons were hardened to 59–62 HRC, they also had similar tensile strengths (at the surface).

The depth of the compressive stress layer is a function of the Almen intensity. It can be increased by increasing shot size and/or velocity. The depth is the location where the residual stress vs. depth curves would cross the neutral axis (into tension) if the positively sloped lines were extended. A greater depth of compression is desired because this layer is what resists fatigue crack growth. Coupons 2 and 4 were shot peened to the same intensity, so that the depth of their compressive stress layers is also essentially the same at approximately 0.18 to 0.20 mm (0.007 to 0.008").

Dual peening. The trade-off to increasing shot peening intensity is that there is additional cold work and material displacement at the point of shot impact. This generally results in less compression right at the surface (depth = 0) and a more aggressive surface finish.

Dual peening is performed to make up for the reduced compression resulting from high-intensity peening. The technique consists of shot peening the same surface twice—peening at a higher intensity is followed by peening at a lower intensity, usually with smaller media. The second peening reduces the degree of cold work at the surface, improving the surface finish, which, in turn, makes the surface more compressed.

Coupon 5 was dual peened. The process specified MI-230H shot at 18 to 20 Almen followed by MI-110H shot at 8 to 10 Almen. The residual stress curve for this coupon (Fig. 7) is approximately 0.025 to 0.05 mm (0.001 to 0.002") deeper than the curves for the coupons single shot peened at 14 to 16 Almen using MI-230H shot.

This would be expected for a carburized gear steel. The surface stress of Coupon 5 (at depth = 0) is the same as that of the other two shot peened coupons. What most likely occurred is that it was less compressed after the first peening step. When the second was performed, the surface became even more compressed, to the approximately 930 MPa (135 ksi) level shown in Fig. 7. Therefore, Coupon 5 would be expected to have the best fatigue performance of the three because it has the most compressive stress throughout its depth. This is particularly evident between 0.08 and 0.20 mm (0.003 and 0.008") below the surface. At 0.10 mm (0.004") below the surface, for example, there is still 1,380 MPa (200 ksi) of compression for Coupon 5, compared with 1,170 MPa (170 ksi) for Coupon 4 and 1,000 MPa (145 ksi) for Coupon 2.

Effect of grinding. Testing of coupons that had been ground gave unexpected results that required further investigation. All coupons were ground at the same time. Grinding was performed using a wheel that had coolant flow. The operator was instructed to remove no more than 0.025 mm (0.001") of stock per pass, for a total of 0.10 mm (0.004") of material removed from each coupon. This appeared to be acceptable grinding practice, and little thought was given to the technique prior to testing.

X-ray diffraction measurements indicated that tensile stresses existed on the surface of the vacuum carburized coupon (Coupon 1) as high as 255 MPa (37 ksi) at 0.013 mm (0.0005") below the surface. At a depth of approximately 0.10 mm (0.004"), the values crossed the neutral axis into compression. These results were immediately questioned. However, retesting at several locations using X-ray diffraction verified that the original values were correct.

The explanation lies in the fact that additional heat was generated when grinding vacuum carburized Coupon 1. The coupon was 1 HRC point harder at the surface and 4 HRC points higher after 0.10 mm (0.004") of stock removal. These values are higher than those for the atmosphere carburized specimen (Coupon 3). Additional heat from an increase in friction resulted in the generation of residual tensile stresses on the vacuum carburized coupon.

This is an excellent example of why it is important to carefully evaluate the amount of heat generated when grinding fatigue-critical parts. It also demonstrates that X-ray diffraction is an excellent tool for determining the residual stress state of components before they enter service.

Test Results Reviewed

This study compared atmosphere and

vacuum carburizing of AISI 8620 gear steel and evaluated the influence of the subsequent manufacturing operations of shot peening and grinding. The primary goal of the study was to determine which carburizing process was more suitable for heavy-duty transmission gears. Gears are subject to both sliding and rolling contact stresses on their flanks in addition to bending stresses in tooth roots. To meet these demanding performance criteria, the steel gears ideally would be hardened for strength and contact properties and have residual compressive surface stresses for bending fatigue resistance.

We concluded that vacuum carburizing is superior to atmosphere carburizing for heat treating heavy-duty transmission gears, and enjoys the following advantages:

• *Higher hardness:* In the coupons tested with X-ray diffraction, the surface, before grinding, was 1 HRC point higher (60 vs. 59 HRC); the subsurface, after 0.10 mm (0.004") stock removal, was 4 HRC points higher (62 vs. 58 HRC).

• *Greater depth of high hardness, ≥ 58 HRC:* In the coupons tested with X-ray diffraction, 58 HRC depths were 0.58 mm (0.023") for vacuum carburizing and 0.20 mm (0.008") for atmosphere carburizing.

• *Greater depth of high hardness, ≥ 58 HRC, at the pitch line and root of actual gears:* 58 HRC depths were 0.81 mm (0.032") for vacuum carburizing and 0.38 mm (0.015") for atmosphere carburizing.

• *Deeper effective case in tooth root of actual gears:* Vacuum, 1.0 mm (0.040"); atmosphere, 0.699 mm (0.0275").

• *Higher surface residual compression (determined by X-ray diffraction of coupons without shot peening or grinding):* Vacuum, 135 MPa (19.6 ksi); atmosphere, 98 MPa (14.2 ksi).

• *Improved consistency between the case layer at the pitch line of the gear flank and gear roots (actual gears):* Vacuum, 0.28 mm (0.011") variation; atmosphere, 0.648 mm (0.0255") variation.

Shot peening. The vacuum carburized and atmosphere carburized surfaces responded equally to shot peening:

• Maximum compressive stress: approximately1,515 MPa (220 ksi).

• Compressive layer depth: approximately 0.18 to 0.20 mm (0.007 to 0.008").

Dual shot peening at first a higher and then a lower intensity resulted in a greater depth of compression by approximately 0.025 to 0.05 mm (0.001 to 0.002"). The surface stress of the dual-peened coupon was very similar, at approximately 930 MPa (135 ksi), to that of the conventionally shot peened coupons. The higher-intensity first peen would have produced a less compressed surface, but the second, lower-intensity peen would have restored compressive stress to the approximately 930 MPa (135 ksi) level. The dual-peened coupon should have significantly better high-cycle fatigue properties than the single-peened coupons.

Fatigue. In terms of fatigue performance, the additional 34.5 MPa (5 ksi) of compression measured for the vacuum carburized coupon (not shot peened or ground) should yield significant increases in gear life under high-cycle fatigue loading, compared with that for the atmosphere carburized coupon.

The study also served as an excellent reminder of the importance of understanding how all manufacturing processes may affect residual stresses and, consequently, fatigue performance. Actual gears must now be tested to ensure that changes to the manufacturing process—involving material, part geometry, heat treatment, shot peening, and/or grinding —will have the same effects in production as those observed in this study.

Acknowledgments

The authors thank Bodycote Thermal Processing, Racine, WI, for atmosphere carburizing and Midwest Thermal-Vac/ECM-USA Inc., Kenosha, WI, for vacuum carburizing of test coupons and gears.

FOR MORE INFORMATION

• Mr. Lindell is corporate engineering metals specialist at
Twin Disc Inc.
4600 21st St.
Racine, WI 53405-3698
Telephone: (262) 554-0640
Fax: (262) 554-2769
E-mail: *lindell.gerald@twindisc.com*

• Mr. Herring is president of
The Herring Group Inc.
P.O. Box 884
Elmhurst, IL 60126-0884
Telephone: (630) 834-3017
Fax: (630) 834-3117
E-mail: *dherring@heat-treat-doctor.com*

• Mr. Breuer is regional director – technical sales at
Metal Improvement Co. Inc.
8201 N. 87th St.
Milwaukee, WI 53224-2804
Telephone: (414) 355-6119
Fax: (414) 355-9114
E-mail:
dave_breuer@metalimprovement.com

• Ms. Matlock is senior materials engineer at
TEC
10737 Lexington Drive
Knoxville, TN 37932-3294
Telephone: (865) 966-5856
Fax: (865) 675-1241
E-mail: *bmatlock@tec-usa.com*

This article is based on "An Analytical Comparison of Atmosphere and Vacuum Carburizing Using Residual Stress and Microhardness Measurements," a paper presented by the authors at the 21st ASM Heat Treating Society Conference, held Nov. 5–8, 2001, in Indianapolis, IN.

This article also appeared previously in the November 2001 issue of *Heat Treating Progress* magazine, published by ASM International. Reprinted with permission.