Selecting the Best Carburizing Method for the Heat Treatment of Gears

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ABSTRACT

A very good compromise between cost and performance is achieved by atmosphere carburizing, the present day *de facto* standard processing method used in the gear industry. A typical workload is shown in Figure 1.

All indications are, however, that the greatest potential for future growth will come in vacuum carburizing. Figure 2 shows a load of gears ready to be charged into a typical vacuum carburizer. This method of carburizing has been shown to offer proven metallurgical and environmental benefits.

For the industry to stay competitive both technologies will be needed in the future. This is to insure that the challenges posed by ever increasing performance requirements in smaller packages and by a new generation of materials and manufacturing methods can be met.

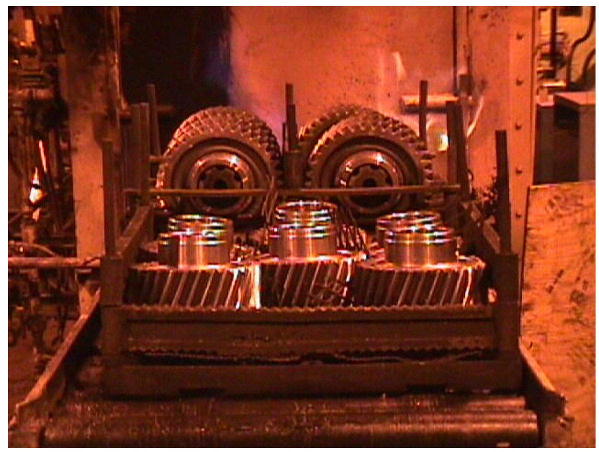

Figure 1: Load of Production Gears (650 lbs net) in Position for Loading into an Atmosphere Carburizing Furnace followed by Oil Quenching.

INTRODUCTION

Of paramount importance today is lowering unit cost that can only be achieved by improved dimensional control and more cost effective manufacturing methods. The benefits achieved by vacuum carburizing can be realized in high volume, critical component manufacturing.

Vacuum carburizing has proven itself a robust heat treatment process and a viable alternative to atmosphere carburizing. Gear manufacturers of heavy duty, off-road transmissions and related equipment such as Twin Disc Corporation have found numerous benefits in substituting vacuum carburizing with high gas pressure quenching for either atmosphere or vacuum carburizing with oil quenching technology. This paper will present scientific data in support of this choice.

Figure 2: Load of Production Gears (650 lbs net) in Position for Loading into a Vacuum Carburizing Furnace followed by High Gas Pressure or Oil Quenching

HISTORICAL BACKGROUND

It is unfortunate that atmosphere and vacuum technology are viewed as competitors instead of as complements to one another. The existing "us versus them" mentality created by constant negative comparisons has hurt both technologies.

In the 1960s the need for better atmosphere control prompted a series of R&D efforts to find a solution. One of these led to the development of vacuum carburizing, viewed as an alternative to atmosphere carburizing providing enhanced metallurgical properties and shorter cycle times. However, it was promoted within the heat treatment industry as a panacea for all the problems of atmosphere carburizing, and, thus, initiated competition between the two technologies.

Had vacuum carburizing proved to be a robust technology at that time, it is generally believed that a significant portion of today's installed equipment base would use this technology. Its failure to achieve commercial success can be directly related to reliability and cost. The creation of soot was the Achilles heel of vacuum carburizing. Perhaps a more accurate statement is that the equipment designs and process parameters of vacuum carburizing were not optimized, and the technology's capabilities oversold to the heat-treating community.

Today these problems have been addressed and sooting is no longer a limitation of the process. New equipment designs, controls, and processing methods assure excellent up time productivity and high volume capacities.

POWER TRANSMISSION COMPONENTS

The application and manufacture of high quality transmission gearing used in demanding applications such as shown in Figures 3 and 4 require careful consideration of a number of critical factors including: component design; material selection; heat treatment method; and the influence of post heat treatment manufacturing operations.

Gearing is subject to both sliding and rolling contact stresses on the gear flanks in addition to bending stress in the tooth roots. The most desirable gear properties to meet these two criteria would be hardened gears for strength and contact properties with residual compressive surface stress for bending fatigue properties.

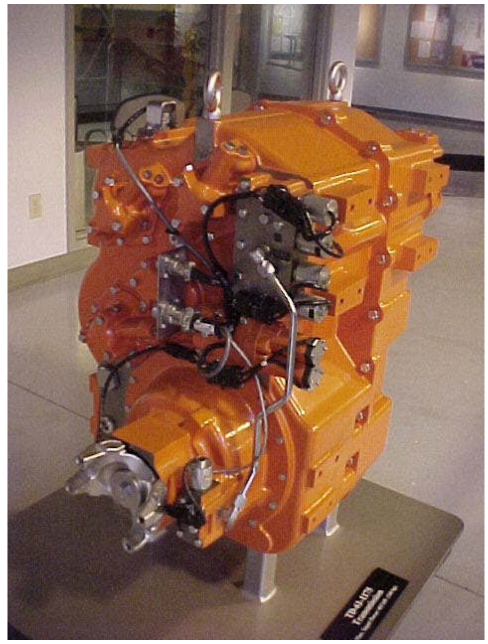

Figure 3: Typical heavy duty Transmission Used for Airport Fire Vehicles.

Fatigue is a major cause of failure in gears. Fatigue failures fall into two classes: tooth root bending fatigue and tooth flank contact related failures. In this work residual stress and microhardness testing were used as indicators to compare the atmosphere and vacuum carburizing processes.

Figure 4: Heavy Duty Marine Transmission Transfer Gears.

The greater the magnitude and depth of compressive stress the greater the ability to improve fatigue properties. A high compressive stress value at the surface helps the component resist crack initiation. The deeper the compressive layer the greater the resistance to crack growth for longer periods of time.

Residual stress values are an important factor in fatigue critical components. Residual stresses are additive with applied stress. Compressive residual stresses are desired as they oppose the applied, repetitive, and undesirable tensile stress that causes fatigue failure. X-ray diffraction methods allow measurement of residual stress levels.

For the purposes of this investigation, the vacuum and atmosphere carburizing processes were studied using x-ray diffraction techniques and microhardness measurements. Specimens of AISI 8620 material were manufactured, carburized by the different methods and subjected to identical post heat treatment operations. Grinding and shot peening were selected as representative.

CARBURIZING PROCESSES

Carburizing of a steel surface is both a function of the rate of carbon absorption into the steel and the diffusion of carbon away from the surface and into the metal. Once a high concentration of carbon has developed on 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, or carbon gradient between the carbon rich surface and the interior core of the metal. The result is a reduction of the carbon concentration at the surface while increasing the depth of carbon absorption.

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

Atmosphere Carburizing

Atmosphere carburizing is an empirically based, time-proven process in which a carbon-rich atmosphere surrounding a workload is used to chemically react with the surface of the parts to allow an adequate quantity of carbon to be absorbed at the surface and diffused into the material.

In atmosphere carburizing parts are heated to austenitizing temperature in an Endothermic or equivalent atmosphere containing approximately 40% hydrogen, 40% nitrogen, and 20% carbon monoxide. Small percentages of carbon dioxide (up to 1 1/2%), water vapor (up to 1%), and methane (up to 1/2%) along with trace amounts of oxygen are also present. This "neutral" or "carrier gas" atmosphere is generally considered neither carburizing nor decarburizing to the surface of the steel.

In order to perform the carburizing process enriching gas is added to the carrier gas atmosphere. The enriching gas is usually either natural gas which is about 90 - 95% methane (CH_4) or propane (C_3H_8). In atmosphere carburizing it is common practice to begin the flow of enrichment gas just after the furnace has recovered setpoint. This practice contributes to case non-uniformity as various parts of the workload are not uniform in temperature and carburize at different rates.

The water gas reaction (Equation 1) is important in the control of the atmosphere carburizing process. Instruments such as dew point analyzers monitor the H_2O/H_2 ratio of this equation while infrared analyzers and oxygen probes look at the CO/CO_2 ratio.

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

In atmosphere carburizing, intergranular oxidation is one of the phenomena taking place as a result of the constant changes occurring in the furnace atmosphere.

This can be explained by considering an alternative form of the water gas reaction (Equation 2). Here we see that 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 with alloying elements such as silicon, chromium, and manganese

$$CO + H_2 = [C] + H_2O \qquad (2)$$

Figure 5 shows results from an actual gear sample that was atmosphere carburized.

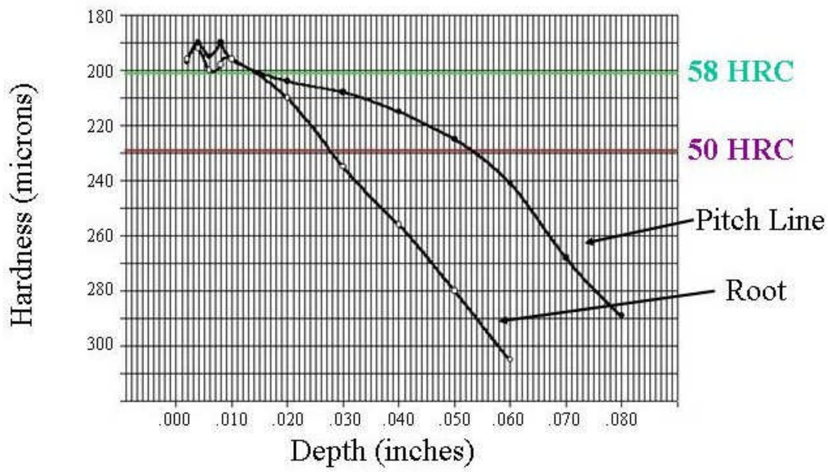

Figure 5: Pitch Line & Root Comparison: Atmosphere Carburized (Oil Quenched) Gear

Results show carburization to an effective case depth (50 HRC) of 0.030” (0.76 mm) in the root and 0.052” (1.33 mm) at the pitch diameter. Of greater significance is the value for the depth of high hardness (≥ 58 HRC), namely 0.014” (0.35 mm) at both the gear tooth pitch line and root. From this depth the hardness values quickly diverge. These results are typical of the vast majority of carburized gears currently in service.

Advantages of atmosphere carburizing include:

- The lowest initial capital equipment investment cost.
- Capability of high volume output using a wide variety of equipment styles, types, and workload sizes. Furnace types include box, pit, mechanized box (integral- and sealed-quench furnaces), pusher, conveyor (mesh belt and cast link belt), shaker hearth, rotary hearth, rotary drum (rotary retort), and carbottom.
- Adequate process control; that is; all of the process variables are understood and reliable control devices are available to provide a measure of process repeatability.
- Capable of being easily automated with recipe and/or part-number control of heat treat cycles.
- Well-understood process problems allowing troubleshooting based on an established theoretical and empirical knowledge base.

The last point is very important. Often in the real world, cost or other considerations mean that problems cannot be avoided, but it is the ability to quickly and easily address the issues that arise, which dictates the success of a given technology. This certainly is one of biggest advantages of atmosphere carburizing.

Disadvantages of atmosphere carburizing include:

- A requirement of knowledge gained through empirically methods is required to achieve repeatable results. This is due to a wide variability in the type of equipment, its operation, maintenance and constantly changing process conditions.
- The need to “condition” equipment if idled or shut down prior to processing work.
- The need for large material allowances for post-processing operations due to accuracy and finish requirements. Case depths typically are specified in wide ranges (e.g. 0.030 to 0.050 in. (0.75 to 1.25 mm) to compensate for cycle induced variability.
- Case depth quality issues; the best part of the case often is lost due to the amount of stock removal required.
- The need to constantly be concerned about safety and fire prevention issues (e.g., fire from combustible gases and quench oils, hot contact surfaces and pinch points).
- The need to monitor environmental pollution issues including air quality (for potentially hazardous gases, such as CO and NOx), water quality (for contamination concerns such as oil, minerals, etc.), waste disposal (quench oils). and safety issues
- Processing techniques that produce non-uniformity of case and carbon profiles throughout the gear geometry (tip-pitch line-root).

It is important to note that a great deal of the non-uniformity of case depth can be avoided if adequate soak time at temperature is used or if load preheating techniques are employed.

Vacuum Carburizing

Vacuum carburizing is a proven method of *pure* carburizing and *pure* diffusion in which carbon penetrates into the surface of the steel being processed without interference from external influences such as gas chemistry or surface contaminants.

Vacuum carburizing is a modified gas carburizing process in which the carburizing is done at pressures far below atmospheric pressure (760 Torr). The typical pressure range for low pressure vacuum carburizing is 1-20 Torr.

The advantage of this method is that the steel surface remains very clean and the vacuum environment makes the transfer carbon to the steel surface faster (higher carbon flux values) since atmosphere interactions such as found in the water gas reaction do not take place. In addition no intergranular oxidation can occur.

The carbon produced by the breakdown of the hydrocarbon gas introduced into the chamber is free to penetrate into the surface of the steel while the hydrogen and residual hydrocarbon byproducts are removed from the system by the vacuum pumps.

The hydrocarbon gases currently being used for vacuum carburizing are acetylene (C_2H_4), propane (C_3H_8) and to a lesser degree ethylene (C_2H_4). Methane (CH_4) is essentially non-reactive at these low pressures, unless the temperature is near 1900 °F (1040 °C).

In vacuum carburizing the breakdown of hydrocarbon gases involve non-equilibrium reactions. This means that the surface of the steel is very rapidly raised to the saturation level of carbon in austenite. By repeating the boost and diffuse steps desired carbon profile and case depth can be achieved.

Depending on the type of hydrocarbon gas used, carbon is delivered to the steel surface via reactions such as

$$C_2H_2 \rightarrow 2C + H_2 \quad (1)$$

$$C_3H_8 \rightarrow C + 2CH4 \quad (2a)$$

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

$$C_3H_8 \rightarrow C_2H_2 + H_2 + CH_4 \rightarrow C + 2CH_4 \quad (2c)$$

$$C_2H_4 \rightarrow C + CH_4 \quad (3)$$

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

Figure 6 shows results from an actual gear sample that has been low pressure vacuum carburized.

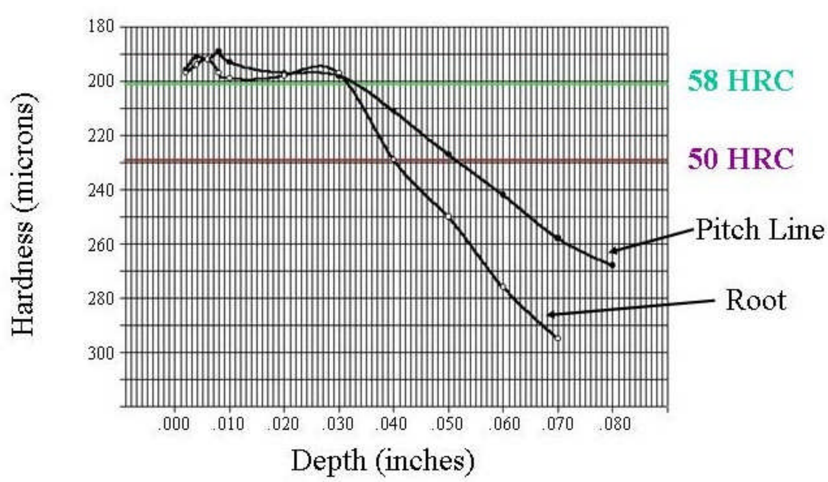

Figure 6: Pitch Line & Root Comparison: Vacuum Carburized (Oil Quenched) Gear

Results show carburization to an effective case depth (50 HRC) of 0.040” (1.00 mm) in the root and 0.052” (1.33 mm) at the pitch diameter. Of greater significance was the value for the depth of high hardness (≥ 58 HRC), namely 0.032” (0.80 mm) at both the gear tooth pitch line and root.

The overall case depth of maximum hardness for the vacuum carburized part is noticeably deeper than the atmosphere carburized part in Figure 5.

One also observes a far greater consistency in the root and pitch line hardness through the depth of high hardness.

Figure 7 below shows an actual gear sample that has been vacuum carburized and high gas pressure quenched. These results, when compared to Figure 5 and Figure 6 allow us to conclude that a more uniform case depth has been developed between the gear pitch line and root.

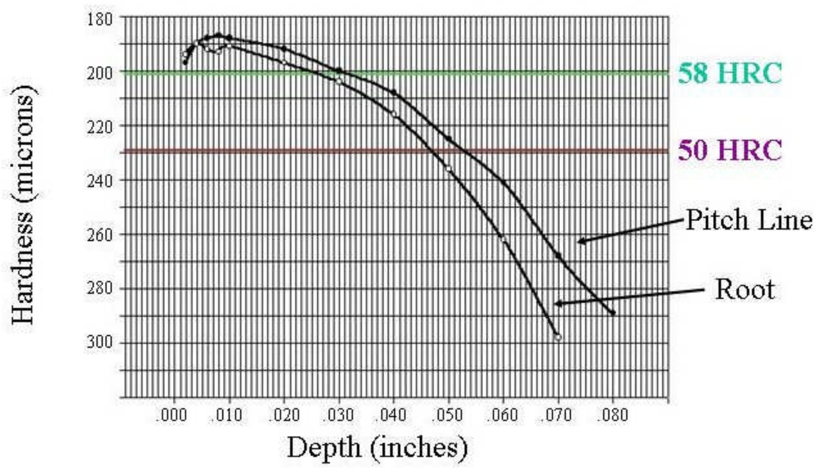

Figure 7: Pitch Line & Root Comparison: Vacuum Carburized (High Gas Pressure Quenched) Gear

This is due in large part to the absence of a vapor layer in gas quenching resulting in a more uniform quenching rate in the gear tooth and root profiles.

Advantages of vacuum carburizing include:

- Absence of intergranular oxidation.
- Capability of higher temperatures due to the type of equipment and the nature of the process.
- Process and cycle flexibility allows a wider variety of materials to be processed.
- Processing methods produce more uniform case and carbon profiles throughout the gear tooth geometry (tip-pitch line-root).
- Easy integration into manufacturing. The process is clean, safe, simple to operate and easy to maintain. Also, working conditions are excellent (that is, there are no open flames, heat and pollution).
- Full automation capability using recipe or part-number control of heat treating cycles.
- Precise process control achieved using computer simulations, which allow adjustments to established cycles.
- Consumption of energy by the equipment and process only when needed due to the nature of the vacuum operation.
- Typically less distortion results provided adequate measures are taken in loading.

Disadvantages of vacuum carburizing include:

- Higher initial capital equipment cost than atmosphere carburizing equipment.
- Part cleanliness is more critical in order to achieve desired results.
- Empirical process control, which requires processing loads to determine optimum settings or to fine tune simulator.
- Formation of soot and tar, which occur due to the type, pressure, and quantity of hydrocarbon gas introduced.

It is important to note that research during the past six years has succeeded in finding combinations of pressure, gas type, and flow parameters to minimize soot and tar formation and eliminate these factors as a concern in the vacuum carburizing process.

Shot Peening

Shot peening is a process that induces a high magnitude, residual compressive stress. It is most effective for parts subject to high cycle fatigue loading as the compressive stress at the surface results in significantly enhanced fatigue life. Figure 8 below illustrates a typical S-N curve for a high cycle fatigue application.

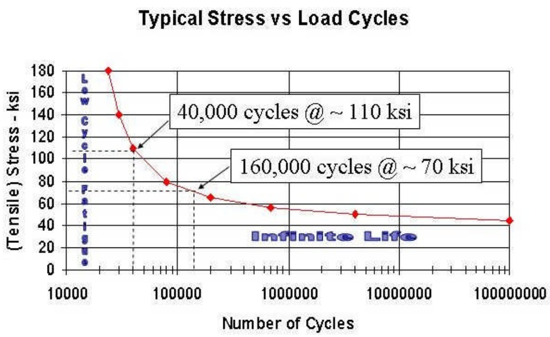

Figure 8: Stress versus Load Cycles

This graph shows that a linear reduction in tensile stress results in an exponential improvement in fatigue life. A 35% reduction in stress - from 110 ksi (759 MPa) to 70 ksi (483 MPa) results in a 400% improvement in fatigue life, - from 40,000 cycles to 160,000 cycles. Additional reductions in tensile stress result in significantly more fatigue enhancement.

The residual compressive stress from shot peening counteracts applied tensile stresses in the material. The compressive stress from shot peening is induced from small, spherical media striking the surface. The impact from each particle stretches the surface enough to yield it in tension. The surface cannot fully restore itself thus producing a permanent compressed state.

Shot peening is a surface treatment that results in a magnitude of residual compression that is ~ 55 - 60% of the material's ultimate tensile strength at the surface where most fatigue cracks initiate. For carburized gears the amount of surface compression is typically 170 - 230 ksi (1173 – 1587 MPa) offering significant improvement in fatigue properties.

TEST METHODS

X-Ray Diffraction

X-ray diffraction measures residual stresses at surface and sub-surface locations in a sample. The method is considered a surface analysis technique since only a few atomic layers are measured. The sub-surface measurements were made by electrochemically removing small amounts of material. These sub-surface measurements were subsequently corrected for stress gradient and layer removal effects using standard analytical calculations.

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 chosen to diffract the (211) planes at approximately 156° 2θ. The area measured was nominally 4 mm in diameter.

TEST PROCEDURE

The following procedure was performed in order to evaluate the influence of atmosphere and vacuum carburizing as well as the influence of shot peening and grinding.

- Five coupons were cut and stamped from the same heat lot of AISI 8620.
- A separate manufacturing process was created for each coupon according to the following stamped identifications:
  - VC: Vacuum Carburize
  - VC & SP: Vacuum Carburize & Shot Peen
  - AC: Atmosphere Carburize
  - AC & SP: Atmosphere Carburize & Shot Peen
  - VC & DSP: Vacuum Carburize & Dual Shot Peen
- The coupons were sent out for vacuum or atmosphere carburizing.
- The coupons were ground to size removing no more than 0.006" (0.15 mm) from the non-stamped side.
- Three of the five coupons were sent out for shot peening.
- All five coupons were sent out for X-ray diffraction analysis on the non-stamped side.

PROCESS COMPARISON

The carburizing parameters used are summarized in Table 1 below:

Table 1
Carburizing Parameters

Carburizing Method	Temperature	Boost Time (minutes)	Diffusion Time (minutes)	Hardening Temperature	Quenching Method	Tempering
Atmosphere	1725°F (940°C)	300	120	1550°F (845°C)	Oil @ 60°C (140°F)	350°F (175°C) 2 hours
Vacuum	1725°F (940°C)	32	314	1550°F (845°C)	Nitrogen gas @ 20 bar*	350°F (175°C) 2 hours

*Note: 1 bar = 14.7 psia

Influence of Carburizing Method

Vacuum carburizing produced a deeper case depth of high (≥ 58 HRC) hardness as seen in Figure 9 showing a comparison of atmosphere and vacuum carburized test coupons.

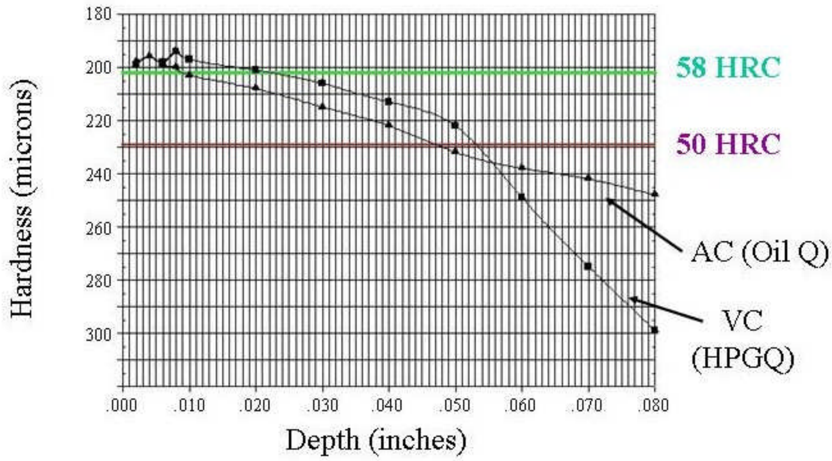

Figure 9: Comparison of Vacuum Carburizing Using High Pressure Gas Quenching and Atmosphere Carburizing Using Oil Quenching

Figure 10 shows a comparison of core microstructure. Samples shown are from the pitch line with the area below the root showing similar results. Today, vacuum carburizing techniques can employ either oil or high pressure gas quenching technology in the range of 6-20 bar using nitrogen, helium, argon or gas blends. A properly designed gas quench system will produce a core microstructure in a heavy section thickness that consists of tempered martensite with some transformation products (bainite and ferrite) present in the microstructure as well.

Atmosphere or Vacuum Carburized
& Oil Quenched Sample.
Core microstructure consists of tempered martensite.
Core Hardness is 37 HRC.

AISI 8620 Gears
Part Weight = 26 lbs.
Load Weight = 500 lbs net

Vacuum Carburized
&Gas Quenched Sample.
Core microstructure consists of tempered martensite and transformation products
Core Hardness is 29 HRC.

Figure 10: Comparison of Core Microstructure

Influence of Shot Peening

Figure 11 shows the residual stress distributions of the carburizing processes followed by grinding with shot peening.

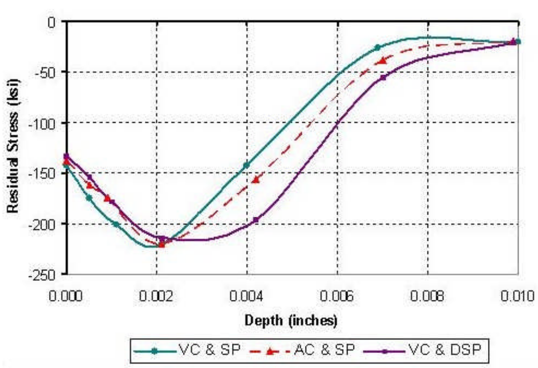

Figure 11: Vacuum and Atmosphere Carburized Ground Samples With Single and Dual Shot Peening

The graph shows that a solid layer of compression exists using all three methods. From a fatigue standpoint, excellent resistance to the initiation and growth of fatigue cracks will result. The tensile stress required for a fatigue crack to develop must first overcome the compressive stress that is ~ 150 ksi (1035 MPa) at the surface and ~ 220 ksi 0.002" (1518 MPa 0.051mm) below the surface.

The three residual stress curves have the representative shape of a carburized and shot peened material. The maximum compressive stress of all three curves is similar and is ~ 220 ksi (1518 MPa). This value is approximately 55 - 60% of the material's ultimate tensile strength at the surface. Since all three coupons were 59 - 62 HRC, they had similar hardness & tensile strength (at the surface). The reason that the curves shown in Figure 11 do not cross the neutral axis is due to the carburization process that induces residual compressive stresses prior to shot peening.

The depth of the compressive stress layer is a function of the intensity or energy of the shot stream. It can be increased by increasing the shot size and/or velocity. The depth is the location where the curves would cross the neutral axis (into tension) if the positively sloped lines were extended. A deeper depth of compression is desired as this is a layer resisting crack growth. The tradeoff to increasing the intensity is that there is additional cold work and material

displacement at the point of shot impact. This generally results in a less compressed surface stress (at depth = 0.000”) and a more aggressive surface finish.
Figure 12 shows visually how increasing the shot peening energy changes the shape of the residual stress curve.

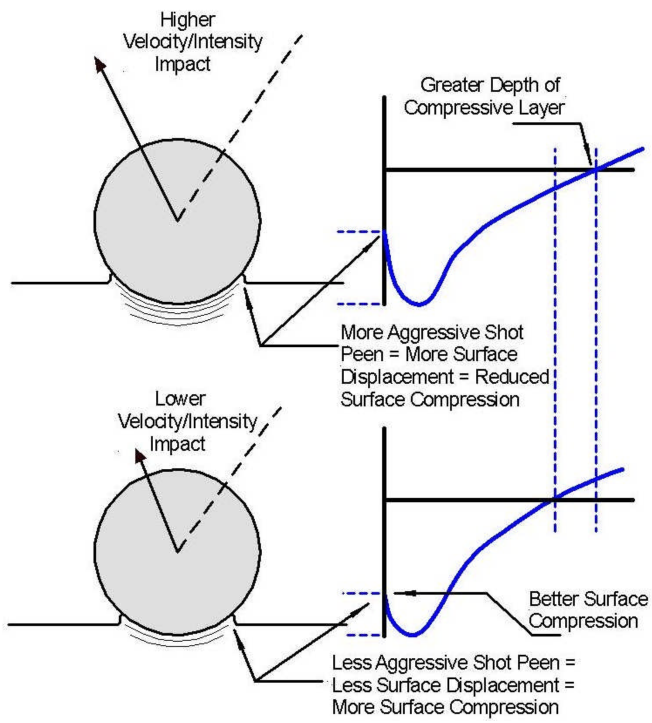

Figure 12: Influence of Shot Peening Energy on Residual Stress

Coupon VC & DSP was dual peened. Dual peening consists of shot peening the same surface twice. First, a higher intensity is utilized and then followed by a lower intensity, usually with a smaller media. The second peening operation is able to reduce the cold work at the surface by improving the surface finish thus making the surface more compressed.

The use of dual shot peening should be weighed via a cost/benefit analysis. Typically, dual peening approximately doubles the cost while offering the potential to double or triple the fatigue life produced by a single shot peen.

An analysis of Figure 11 indicates that the best fatigue performance should come from the coupon dual shot peened as it has the best combination of surface compression and compressive layer depth properties.

This is particularly evident between 0.003” (0.076 mm) and 0.008” (0.203 mm). At 0.004” (0.102 mm) below the surface there is still 200 ksi (1380 MPa) of compression for the VC & DSP coupon versus 170 ksi (1173 MPa) for coupon AC & SP and 145 ksi for coupon VC & SP.

The dual shot peened coupon should result in a significant increase in high cycle fatigue properties over the (single) peened coupons.

In terms of fatigue performance, the additional 5 ksi (34.5 MPa) of compression measured in the vacuum carburizing coupon (without shot peening or grinding) should yield significant increases in gear life under high cyclic fatigue loading over the atmosphere carburized coupon.

CONCLUSIONS

The primary focus of this study was to determine which carburizing process was more suitable for heavy duty transmission gears manufactured from AISI 8620 steel. Vacuum carburizing was found superior to atmosphere carburizing in this instance as the data in Table 2 indicates, for the following reasons:

- Higher Surface Hardness
- Greater Depth of High Hardness
- Deeper Effective Case Depth in the Tooth Root
- Higher Surface Residual Compression
- Uniformity of Case at Pitch line of the Gear Flank & Roots

Table 2: Comparison of Atmosphere and Vacuum Carburizing Results

Process	Surface Hardness (before grinding)	Surface Hardness (after grinding)	High (≥ 58 HRC)Hardness (coupons)	High (≥ 58 HRC)Hardness (gears)	Surface Residual Compression (ksi)	Deviation of Case at Pitch Line
Vacuum	60 HRC	62 HRC	0.023”	0.032”	19.6	0.011”
Atmosphere	59 HRC	58 HRC	0.008”	0.015”	14.2	0.026”

Both the atmosphere carburized and vacuum carburized surfaces responded equally to the shot peening treatment.

- Maximum compressive stress: ~ 220 ksi (1518 MPa)
- Compressive layer depth: ~ .007” - .008” (0.178 - 0.203 mm)

The dual shot peening resulted in a greater depth of compression by ~ .001” - .002” (0.025 - 0.051 mm). The surface stress of the dual peening was very similar to the previously discussed shot peened coupons at ~ 135 ksi (932 MPa). The (higher) first peen would have resulted in a less compressed surface but the secondary peen further compressed it to ~ 135 ksi (932 MPa).

RECOMMENDATION

Testing of actual gears must be performed to conclude with certainty that changes to the manufacturing process (material, geometry, heat treatment, shot peening, grinding) will yield benefits such as those observed in this study.

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