# Back To Basics

# Achievable Carburizing Specifications

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**Abstract:**
A widespread weakness of gear drawings is the requirements called out for carburize heat treating operations. The use of heat treating specifications is a recommended solution to this problem. First of all, these specifications guide the designer to a proper callout. Secondly, they insure that certain metallurgical characteristics, and even to some extent processing, will be obtained to provide the required qualities in the hardened gear. A suggested structure of carburizing specifications is given.

In spite of widespread understaffing in engineering departments of gear manufacturers, gear drawings are reasonably well prepared insofar as design is concerned. However, in the very important matter of gear materials and their heat treatment, the situation is very different, especially for gears calling for case-hardening heat treatments.

The most obvious shortfall is either the quality of or the total absence of suitable heat treating specifications, the purpose of which are to facilitate obtaining the desired mechanical and metallurgical qualities in the metal. This is

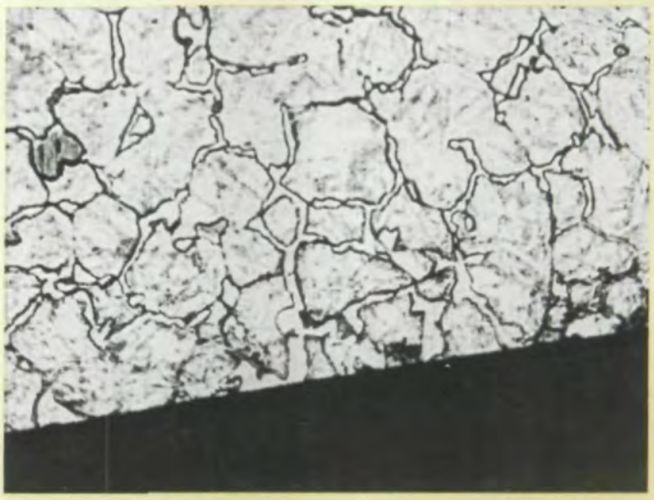

Fig. 1 – Surface microstructure of a failed tooth from a 4 DP low and reverse pinion.

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understandable because few engineering departments in the USA have the budget to carry personnel knowledgeable in metallurgy. The result is the common practice by many design groups of reducing design stresses (overdesigning) so as to get by with questionable material and heat treatment engineering.

Gear designers should be aware of this practice in regard to the heat treatment of gears: It is relatively easy to produce a high quality gear when the requirements are known, as in a specification. It is nearly impossible to produce a so-called medium quality gear. When heat treating quality is reduced, it does not come down uniformly, but in a highly erratic manner. This usually results in a gear wherein some teeth may show high metallurgical quality, some borderline quality, and some very poor quality. This latter type often fails prematurely. Without suitable heat treating specifications, factors such as microstructure can go out of control undetected, resulting in an entire gear being seriously defective. (See Figs. 1 and 2.)

Here is what happened to a Fortune 500 company when design stresses were reduced to 200,000 psi in contact and 65,000 psi in bending to accomodate poor metallurgical quality. This firm was losing market share, and top management finally asked the sales department: "Why?" The answer received was: "Too many field failures." Research revealed that in a period of 25 years there were 1048 instances of major premature failure. For each failure both engineering and metallurgical investigations were made. The fault study revealed the following:

| | Fault |
|---|---|
| Engineering | 70.0% |
| Defective Material | 9.6 |
| Defective Heat Treating | 15.2 |
| Defective Manufacturing | 5.2 |

The engineering department selected materials and specified heat treatments for which it had inadequate in-house specifications. The heat treating specification for carburizing of gears was particularly lacking, as shown below:

1) Carburize at 1650° to 1700°F
2) Cool to 1500° to 1550°F in the carburizing furnace.
3) Quench in oil

Obviously, merely having specifications was no assurance of getting a quality product.

Figs. 1 and 2 show microstructures of two of the company's gear failures. Fig. 1 is the surface microstructure at 500X with a 2% Nital etch of a failed tooth from a 4 DP low and reverse pinion. This failure by tooth breakage occurred after only 148 hours of operation. The reason was the lack of strength and toughness brought about by the carbide network. Fig. 2 is the microstructure at 500X of a 2 DP final drive pinion where failure by pitting occurred in approximately 900 hours. The reason for this failure was the large amount of dark etching quenching pearlite (often referred to as bainite).

The materials laboratory in this firm was used only for inspection of incoming material, technical control of heat treating, and failure analysis. This is quite typical. About 60% of the failures were carburized gears. Most of the gear failures were material and heat treatment selection errors due to incomplete specifications.

Fig. 2 – Microstucture of a 2 DP final drive pinion which failed after 900 hours because of pitting.

When proper heat treating specifications are available, they serve at least five important functions:

1) They insure, insofar as possible, that the important qualities counted on by the designer are provided by the heat treater.

2) They make it clear to the heat treater what is required from him.

3) They assist the designer in making the correct callout.

4) They permit heat treating changes to be made on large numbers of drawings with a minimum of effort.

5) They reduce drawing clutter.

The proposed specification format contains some of what would normally be considered material and processing standards. These might be considered out of place, however, the author believes that they should be included because 1) Details of heat treating processing can significantly affect engineering properties, including uniformity of quality in its broadest sense, and 2) Most firms do not have materials and processing standards, so a properly prepared heat treating specification can, at least in part, serve this purpose.

A complete carburizing specification should, as minimum, contain the following 15 articles:

I. Scope
II. Application
III. Premachining Heat Treatment
IV. Stress Relieving
V. Carburizing
VI. Hardening
VII. Tempering
VIII. Magnetic Particle Inspection
IX. Cleaning
X. Straightening
XI. Deep Chilling
XII. Metallurgical Requirements
XIII. Rework
XIV. Records & Reports
XV. Drawing Callout

The purpose of the scope article is to give a broad description of the type of heat treatment for which it is intended; e.g., carburizing. A second function is its use in calling out certain corollary specifications, such as one for acceptable and unacceptable microstructures. Here is a suggested scope article for a carburizing specification:

**I. Scope:**

> This specification covers the requirements for a carburize and harden heat treatment for parts made from 9310 steel and is further qualified by AGMA-XXX (Microstructure Control).

The author believes that carburizing specifications can be written that are suitable for more than one grade of steel; e.g., 8620, 8720, and even 8822. The heat treating characteristics of 9310, however, are so different that a separate specification is preferred. Also, by combining many steels into one specification, the advantage of easily changing the requirements for one grade, shown on many drawings, is lost.

**II. Application:**

> This specification is intended to be used for parts such as gears and shafts made from 9310 steel. For a life of $10^8$ cycles in rolling contact fatigue, a maximum design stress of 265,000 psi shall be used. A maximum bending stress for the same life of 85,000 psi is permissible. A part made per this specification provides maximum toughness. With the 9310H grade of steel applied, this heat treatment will provide a core hardness in the centerline of gear teeth at the whole depth location of 28 Rockwell C minimum. This is assuming a quench vigor of at least H = .35.

Unpredictable distortion in heat treatment causes many problems with parts such as gears. These are rework, scrap, excessive noise, and, of course, premature failure. There are two processing steps that can be taken to minimize this risk. First is a suitable premachining heat treatment. This insures that the microstructure is of maximum uniformity from one lot to the next, with accordant minimum distortion scatter. This treatment also removes stresses, from cold straightening of the raw material. Finally, it can be used to optimize machinability. Here is a suggested article:

**III. Premachining Heat Treatment:**

Before any machining except sawing of bars to length, all material heat treated to this specification shall have been normalized from 1740° to 1760°F and then tempered for four hours at 1140° to 1160°F. After cooling to room temperature, clean by sandblasting or a chemical means.

A second source of unpredictable distortion is the stresses developed in the material from cold working the surface in operations such as heavy turning, boring, and even rough hobbing. These stresses can be removed by a stress relieve before finish hobbing. A suggested stress relieve article is as follows:

**IV. Stress Relieve:**

(a) For parts requiring maximum distortion control, a stress relieve after rough machining is required. When this is the case a note will appear on the drawing as follows: STRESS RELIEVE AFTER ROUGH MACHINING.

(b) Stress relieving shall be done by heating the parts to 1000° to 1050°F and air cooling (no soak required).

(c) Cleaning, if necessary, after stress relieving shall be done by sandblasting or chemical means.

The actual carburizing operation is of major importance in the heat treatment of gears because the carbon content and its distribution in the carburized case affects these engineering qualities: strength (static and dynamic), toughness, pitting resistance, case crushing strength, wear resistance, sensitivity to grinding burn and cracks, and operating noise.

The author regrets to report that even with an operation of this importance, case carbon control has slipped in the past several years. This has been in a large part due to the widespread use of two devices: the oxygen probe atmosphere controller and direct reading spectrographs for case carbon analysis.

The problem with the oxygen probe is really threefold. First, it is a very delicate device, subject to damage and deterioration. Its readings are really in millivolts (0.001 volt). One millivolt is approximately 0.01% carbon in the carburized case on 9310 steel at 1700°F. Second, most oxygen probe auxiliaries are calibrated for a 20% carbon monoxide atmosphere (enriched endothermic gas). Often the atmosphere is changed to nitrogen and methanol without recalibration. Third, oxygen probes are not very reliable with case carbon levels below 0.80% or temperatures below 1400° F.

The problem with the spectrograph for carbon determinations is the lack of accuracy which at best is ± 0.05%. The preferred analytical procedure for carbon is combustion analysis of chips turned from a sample of the same steel as the parts being carburized.

Beyond these problems, many heat treaters have forgotten the fact that the oxygen probe reads carbon potential, but steels carburize to different levels, as shown in Table 1 for a 0.8% carbon atmosphere for 18 hours at 1700°F.[1] Because of these problems, the carburizing article in a specification must call for strong measures to insure proper case carbon control.

Insufficient case carbon content usually results in deficient case microstructure and/or low case hardness, which often results in pitting and an increased tendency to score. Excessive case carbon tends, first of all, to form a continuous network as shown in Fig. 1. This can make a gear tooth brittle and weaker by as much as 30%. Excessive case carbon can also result in excessive retained austenite, which adversely affects pitting life. Insufficient case depth invites case crushing, depending, of course, on the core hardness. Wear resistance increases with carbon content. A good rule to follow on case carbon is to specify no more than is necessary to achieve the required hardness. With most gear steels this content is from 0.60 to 1.00%

**Table 1**

| Type Steel | Case Carbon Content | |
|---|---|---|
| | At .002 Depth | At .007 Depth |
| 1018 | 0.80% | 0.75% |
| 8115 | 0.80 | 0.74 |
| 8620 | 0.77 | 0.71 |
| 4718 | 0.80 | 0.74 |
| 4620 | 0.72 | 0.66 |
| 4820 | 0.67 | 0.63 |
| 9310 | 0.73 | 0.68 |

Following is a suggested article for the carburizing operation.

**V. Carburizing:**

(a) Carburizing shall be done in a furnace that is tight enough to maintain a prescribed carburizing atmosphere. The furnace shall also be equipped with au-

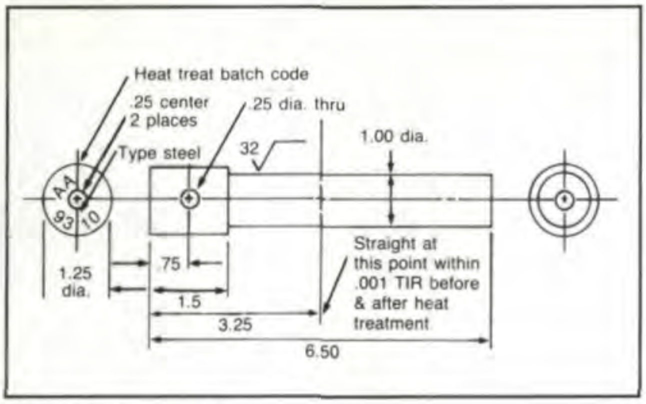


Fig. 3 – Step-turn sample.

tomatic temperature control and fans for circulating the atmosphere.

(b) The atmosphere shall consist of a mixture of endothermic and natural gasses automatically controlled by a suitable carbon potential device. When AGMA-XXX Grade A is called out on the drawing, there shall be at least one backup arrangement to insure that the desired carbon content is obtained. For example, an oxygen probe plus a dew point check, plus carbon steel progress specimens to be examined microscopically, and a step-turn sample as shown in Fig. 3.

(c) At least one step-turn sample as shown in Fig. 3 shall be charged with each furnace load, and conformance determined by combustion tests on chips turned from such a sample that has been both carburized and hardened with the parts.

(d) The hardened sample shall be tempered in a neutral material such as lead, bismuth, argon, or vacuum for two hours at 1200° to 1250°F to provide for the proper machinability to make the required chips.

(e) After the sample has been checked for straightness, the first cut shall be 0.0025" deep on a side. Additional cuts shall then be taken 0.005" deep on a side, until at least the minimum case depth specified has been reached. Chips from each cut shall be kept separate in properly marked envelopes.

(f) A carburizing medium prepared from nitrogen and methanol may be used so long as the oxygen probe control is calibrated for its use.

(g) The carburizing temperature shall be 1700°, ± 20°F unless otherwise specified on the part drawing. For case depths over 0.030 inch the carburize diffuse procedure is preferred. Total penetration is $0.025\sqrt{T}$ where T is the time in hours at 1700°F.[2]

(h) The maximum case carbon shall be at the surface of the parts and the sample, and shall be from 0.75% to 0.85%. For AGMA-XXX Grade B gears, spectrographic carbon results from the surface of a suitable sample of 9310 steel are acceptable.

(i) A mutually agreeable sampling plan shall be worked out for parts run in a continuous carburizer.

(j) The duration of the carburizing cycle shall be such that the specified case depth is retained on the parts after finish grinding, leaving at least 0.70% minimum carbon on the surface.

(k) The minimum case depth, unless experience has indicated otherwise, shall be determined via case crushing calculation per AGMA-218 Section 14.

(l) The tolerances on case depth for 9310 steel are shown in Table 2.

**Table 2**

| Minimum Case Depth (Inch) | Plus or Minus Tolerance (Inch) |
|---|---|
| Up to 0.030 | 0.005 |
| Over 0.030-050 | 0.0075 |
| Over 0.050-0.070 | 0.010 |
| Over 0.070-0.100 | 0.015 |
| Over 0.100 | 0.020 |

(m) At the conclusion of the carburizing cycle, the parts shall be cooled to black in a protective environment.

After the carburizing operation, the next step in heat treating is the hardening. It will be noted in the following article (VI) that the author calls for a carburize-reheat harden type of treatment and has a preference for it over direct quenching. This type of treatment give maximum assurance for freedom from micro-cracks with attendant loss in bending fatigue qualities, as well as a reduction in the amount of retained austenite, and as a result, higher case hardness and resistance to pitting. The lower amount of retained austenite results in the best size stability in final manufacturing operations and field usage. These are both serious problems when direct quenching 9310 steel. Also, some manufacturers have found that the cost of a carburize-reheat heat treatment is no more than direct quenching. However, suitable furnace equipment must be available.

**VI. Hardening:**

(a) Parts shall be heated to a temperature of 1520° to 1540°F and then oil quenched.

(b) Reheating shall be done in an environment such that the surface carbon content of the parts is maintained within that specified for carburizing.

(c) The carburizing sample shown in Fig. 3 shall accompany the gears through both the carburizing and hardening cycles for AGMA-XXX Grade A and combustion analysis used. For AGMA-XXX Grade B the sample shall similarly pass through both the carburize and harden operations; however, spectrographic analysis may be used.

(d) Direct quenching from the carburizing furnace is not permitted.

(e) The preferred quenching oil should have a viscosity of 80 to 120 SUS at 100°F and be maintained at a temperature of 90° to 120°F.

*After quenching it is customary to wash and draw* carburized gears. The wash operation is usually done with a hot alkaline or solvent emulsion solution to remove the residual quench oil and some of the other debris from the heat treating operations. The draw is thought to reduce some undesirable stresses and transform some of the retained austenite to improve grinding qualities. The author is not aware of any work to substantiate this thinking, but it is known that a low temperature draw, e.g., 350°F, reduces the residual compressive stresses in a carburized case by several thousand psi. However, it is probably well to include a temper operation in a carburizing specification as follows:

**VII. Tempering:**

Unless otherwise specified on the part drawing, wash free of quench oil and other heat treating debris and temper for two hours at 325° to 350°F and air cool. Note: If magnetic particle or dye penetrant inspection is required for the part, it shall be done immediately after this operation or after finish grinding.

Large non-metallic inclusions on the flanks (faces) of carburized gear teeth can lead to premature failure. The most common mode of failure is one or more teeth breaking out at the root fillet. This failure occurred in only 725 hours; it was caused by a large alumina inclusion in the surface of the root fillet.

Inclusions in the tooth flanks can also be sites for pitting failures to commence.

To avoid having to make a drawing callout, an article as follows is suggested for magnetic particle inspection:

**VIII. Magnetic Particle Inspection:**

AGMA-XXX Grade A gears shall be 100% inspected using a wet flourescent process as set forth in AGMA-XXX. Grade B gears shall be similarly inspected, but on a formal sampling plan.

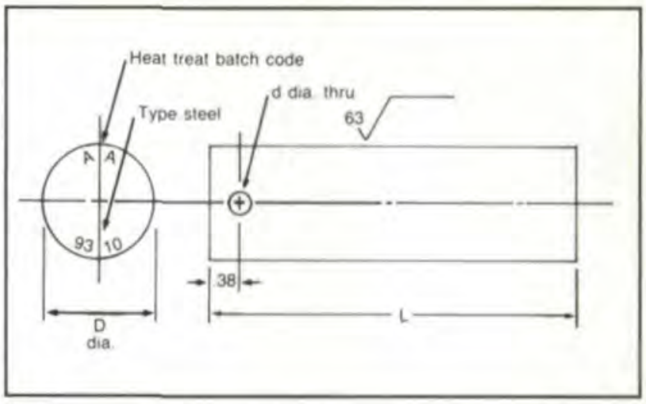


Fig. 4

After washing and tempering, many carburized gears still do not have an acceptable appearance, so it is customary to blast clean them with sand, shot, or other abrasive material. This operation also tends to finish the deburring operation. If soft shot of 45 to 50 Rockwell C hardness is used, the blasting will slightly reduce the residual compressive stresses in the carburized case. Here is a suggested cleaning article:

**IX. Cleaning:**

After cooling to room temperature, clean the parts by shot or sand blasting. Shot size shall be S-330 maximum. Grit blasting is not permitted.

At some time after hardening, especially if a quench press is not available, it is sometimes necessary to straighten carburized parts. This operation can be damaging to the parts' usefulness for the following reasons: 1) The hard case might be cracked, which could lead to premature failure from this defect; 2) The desirable residual compressive stresses in yielded areas of the part are eliminated; hence, long life bending and/or torsional fatigue qualities are reduced; 3) The part can be in an unstable condition, likely to return at least partially, to its unstraightened shape when put in service.

Because straightening is such a potentially damaging and expensive operation, everything practical should be done to eliminate the need for it. When it is still necessary, a reasonably satisfactory solution to the problem is to call for all straightening to be done hot, followed by 100% magnetic particle inspection for cracks. A suggested straightening article is as follows:

**X. Straightening:**

Parts heat treated to this specification shall only be straightened hot; i.e., at 325° to 350°F followed by air cooling to room temperature. All parts shall then be magnetic particle or dye penetrant inspected for cracks.

A practice that is usually the result of loss of control of the carburizing process with excessive case carbon is the necessity of deep chilling to obtain the specified case hardness. The reason for this is the retention of excessive amounts of austenite. Deep chilling transforms a large portion of this austenite into martensite. However, as reported by deBarbadillo, et al.,[3] this results in about a 25% loss in bending fatigue strength. So the following is recommended:

**XI. Deep Chilling:**

Unless permitted on the part drawing, deep chilling of parts heat treated to this specification is not permitted.

In a carburized part there are a number of metallurgical characteristics that provide evidence of proper heat treating. These should be part of a carburizing specification as shown below:

**XII. Metallurgical Requirements:**

(a) The surface hardness of parts after proper surface preparation shall be 59 to 63 Rockwell C measured at the test location shown on the drawing. Note: When the specified case depth is less than 0.030 inch, the surface hardness shall be 90 to 92 Rockwell 15-N.

(b) The tips and flanks of gear teeth shall be file hard to a medium mill bastard file (Nicholson or equal).

(c) The case depth shall be determined for each heat treating lot, and on gears is that distance measured normal to the surface at the LPSTC inward to where the equivalent of 50 Rockwell C occurs.

(d) If it is impractical to cut a gear, samples machined per Fig. 5 from 9310 steel and run with the parts may be used to measure case depth and evaluate microstructures. This work shall be done on a 0.25 inch thick transverse slice from the center of the specimen as shown in Fig. 4. The dimensions of the test specimens are shown in Table 3.

(e) The microstructure at the surface of a gear shall be examined at 400X to 500X at the LPSTC location midway between the ends of the teeth looking for microcracks, network carbide, and quenching pearlite (often referred to as bainite). No micro-cracks or subsurface quenching pearlite are permitted. Also carbide network is not permitted. If a gear cannot be cut, the specimen from Paragraph XII. D can be used for microstructure evaluation.

(f) The core microstructure shall indicate that the part had been properly austenitized for hardening with no blocky ferrite visible at 400X to 500X.

(g) The etchant for microscopic examination shall be 2 to 3% Nital. The etching time to detect micro-cracks and quenching pearlite is very short, usually only 2 to 4 seconds. In order to bring out network carbide and blocky ferrite in the core, the time will usually be from 5 to 7 seconds.

**Table 3**

**(In inches)**

| Gear Pitch | Diameter (D) | Diameter (d) | Length (L) |
|---|---|---|---|
| 1 and Coarser | 3.00 | 0.25 | 6.00 |
| Finer than 1 to 3 | 1.50 | 0.25 | 5.00 |
| Finer than 3 to 8 | 1.00 | 0.25 | 4.00 |
| Finer than 8 | 0.50 | 0.13 | 2.00 |

One of the most serious situations that can develop, which adversely affects the quality of carburized gears, takes place when parts do not meet drawing requirements and it is decided that they are salvageable by re-heat treating (rework). This is a potentially serious problem because a number of things can go wrong. For example: 1) Every time a gear is heated, it becomes more distorted; 2) If a hardened gear is charged into a hot furnace, it might crack; 3) If the carburized case depth is shallow, carburizing a second time just about doubles the case carbon content, because of the "super carburizing" effect. This can result of excessive retained austenite or a carbide network as shown in Fig. 1.

Accordingly, the following article is recommended:

**XIII. Rework:**

(a) All heat treating rework shall be approved by the design control.

(b) A written procedure shall be prepared for all rework.

(c) All reworked parts shall be suitably marked so that retrieval, if necessary, is possible.

The heat treater of high quality carburized gears should be in a position to verify, by examination of a part or samples, that specification requirements have been met on each batch processed. This should include tests for case carbon content, case depth, and case and core hardness. Test results should be suitably recorded and reports made as suggested below:

**XIV. Records and Reports:**

The heat treater shall perform, or have performed, tests to show compliance with this specification. He shall maintain records of these test results traceable to part number, order number, and heat treat batch code.

For AGMA-XXX Grade A gears, for each batch code, the heat treater shall provide the purchaser of the heat treating service, or the design control of the parts with a report of tests run including photomicrographs at 400X of the case surface and the core.

No matter how well heat treating specifications are prepared, if they are not properly called out on the drawing, confusion, as a minimum, is the result. Sometimes rework, scrap, and even premature field failures occur for this reason. Accordingly, it is suggested that a drawing callout article as shown below be included in a carburizing specification:

**XV. Drawing Callout (For design use only):**

(a) Heat Treatment: AGMA-XXX Grade A
Case Depth: .XXX-.XXX

or (b) Heat Treatment: AGMA-XXX Grade B
Case Depth: .XXX-.XXX

or (c) Heat Treatment: AGMA-XXX Grade A
Case Depth: .XXX-.XXX

STRESS RELIEVE AFTER ROUGH MACHINING

There are two additional factors that are important in obtaining heat treating of the prescribed quality. They are 1) The heat treater must have suitable basic equipment and systems in place for both production and quality control, along with personnel dedicated to doing the specified work. A procurement policy for heat treating that favors only price usually results in much job movement, and is discouraging to suitable capital investment in new facilities; and 2) There must be a harmonious relationship between the organization that designs the parts, the one that machines them, and the one that does the heat treating.

To properly carburize irregular parts such as gears, the carburizing gas must be vigorously circulated with hot fans. Trays, baskets, and fixtures must be available to hold and position parts so that a uniform flow of carburizing gas can take place in and around parts. Proper fixturing also minimizes distortion due to sagging at temperature. Gear teeth must not touch each other, nor should they touch a basket or fixture. A high percentage of quench installations lack vigor and/or uniformity and many loads that are quenched are too massive and tightly packed. It is suggested that heat treaters test their quenches for H value as set forth on page 43 of the March, 1985, issue of *Heat Treating* magazine. An H value of 0.50 indicates a well agitated oil quench.

A gear heat treater must be properly equipped with well maintained quality control equipment. This includes not only that for temperature and atmosphere composition but also for case carbon content, case depth, hardness, and microstructure. He should be in a position to submit a report of his tests showing compliance with the specification requirements.

The first step in making a good gear is having a complete and accurate drawing in terms not only of dimensions, tolerances, and finishes, but metallurgical qualities as well. Suitable heat treating specifications play an important role in making drawings complete. To prevent a major duplication of effort and a flood of new specifications to heat treaters, it is suggested that AGMA consider publishing heat treating specifications.

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3. J.J. DEBARBADILLO, "The Effect of Impact Prestressing on the High Cycle Fatigue Resistance of Carburized Gear Steels," SAE International Automotive Engineering Congress, Detroit, Michigan, January 8-12, 1973.



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