GEAR HEAT TREATMENT
PART II

Heat treatment depends on the material and the property profile required.

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GEAR HEAT TREATMENT TODAY

Today, atmosphere carburizing of gears is the de facto standard by which all other hardening techniques, including induction, are measured. The process will continue to be a dominant technology well into the future due in part to its proven results, wide acceptance, high productivity capability, energy choice (primarily gas), and an established equipment and empirical knowledge base.

It is important to note that atmosphere carburizing of gears can be made better through techniques such as preheating of loads to minimize case depth variation, and improved atmosphere control methods such as multi-gas analyzers. Vacuum carburizing, by comparison, has been slow to make significant in-roads but is rapidly gaining momentum due in part to its appeal as a "CNC" heat treatment technique where the knowledge base resides in the equipment rather than in the operator.

Process selection

Process selection is one of the important considerations in gear heat treatment today. It is often dictated to us by existing heat treating equipment or machine tools and these can play a major (negative) role in the resultant microstructure — that is, the case, core, and surface properties obtained.

For example, off-highway transmission gears, made of AISI 8822H material (Fig. 1) and weighing 12 kg (26 lb) each, required carburization to an effective case depth of 1.27 mm (0.050 in.) with a surface carbon content of 0.85%. An as quenched hardness of 65 to 67 HRC was desired, tempered back to 58 to 64 HRC. The core hardness requirement was 28 to 44 HRC.

Fig. 1 — Off-highway transmission gear.

Although these gears have been atmosphere carburized and press or plug quenched for years, today an alternative technology, vacuum carburizing with high pressure gas quenching is being specified. The use of variable gas pressure and flow techniques has successfully replaced oil quenching. The process parameters (Fig. 2) used for these gears can produce different core microstructures (Fig. 3) and different case depth profiles (Fig. 4). With high pressure gas quenching, the core hardness can be

Process parameter	Carburizing method: Atmosphere	Carburizing method: Vacuum
Temperature	940°C (1725°F)	940°C (1725°F)
Boost time	300 min.	32 min.
Diffusion time	120 min.	314 min.
Hardening temperature	845°C (1550°F)	845°C (1550°F)
Quenching method	Oil @ 60°C (140°F)	Nitrogen gas @ 20 bar
Tempering temperture	175°C (350°F)	175°C (350°F)
Tempering time	2 h	2 h

Fig. 2 — Carburizing process parameters.

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Fig. 3 — Core microstructures. Microstructure is martensite with a core hardness of 44 HRC (top). Microstructure is primarily martensite with bainite and ferrite transformation products present (bottom). Core hardness is 28 HRC.

varied from the upper end (42 to 44 HRC) to the lower end (28 to 32 HRC) of the specification. The designers often desire lower core hardness in certain applications since it improves the performance of these gears in service. In addition, the "depth of high hardness", that is the area of hardness equal to or greater than 58 HRC is retained by vacuum carburizing so that the best part of the case is not completely removed by postgrinding operations. Finally, dimensional variation is kept to a minimum by gas quenching, avoiding press or plug quenching and minimizing secondary operations.

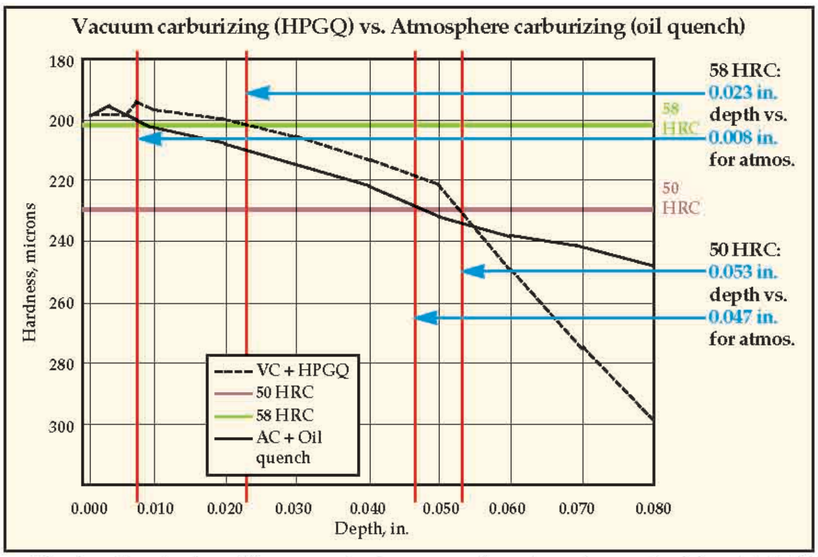

Fig. 4 — Case depth profiles are greater for vacuum than atmosphere carburizing at both 58 and 50 HRC levels.

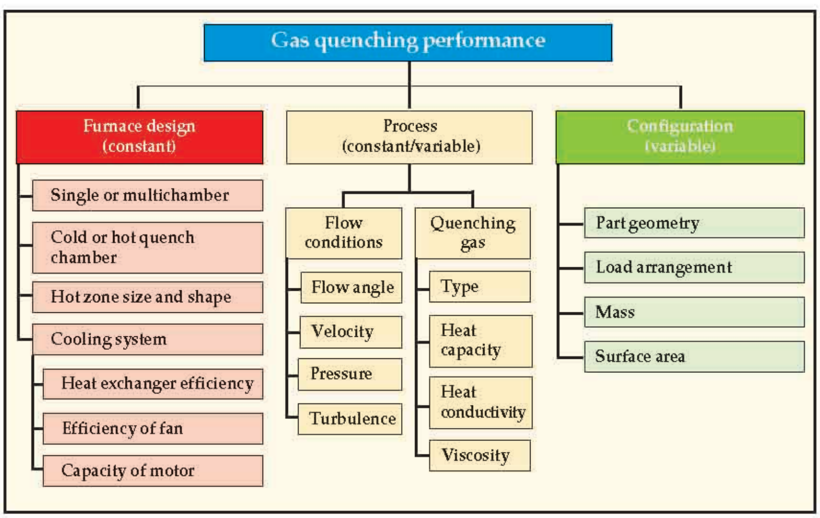

Fig. 5 — Factors influencing quenching.

• *Quench selection.* Dimensional change in gearing is to a large extent a function of quenching method and medium (air, gas, oil, polymer, salt, water, brine) and can be influenced by the choice of posthardening treatments such as cryogenics.

Carburizing and carbonitriding processes require rapid quenching to achieve hardness. Both heating and quenching cycles will result in dimensional changes. The amount and type of size variation depends on the mass and geometry of the gear. If not properly understood, excessive variation can occur to the point where some or all heat treated gears may have to be scrapped. Of equal concern, post heat treatment grinding used to restore tooth accuracy may be so deep as to remove the depth of high hardness in the case. Normalizing of raw material is also recommended to minimize dimensional variation.

• *Quench flexibility.* An almost infinite variety of gear shapes and sizes demands flexibility not only in the heat treatment process, but also in the method of quenching. The number of gears run in a load can vary from a single piece to many hundreds or even thousands. Today, material changes are often necessary to keep up with performance demands of new designs. All of these factors require different techniques that are a combination of uniform, powerful, and/or controlled quenching to achieve the expected results: a tougher, harder, and more predictable part.

Both vacuum and atmosphere carburizing methods can benefit from the use of high gas pressure quenching technology. Equipment designs continue to evolve and are replacing many of the traditional oil quench systems.

In addition to the normal variables (Fig. 5) involved with high gas pressure quenching, special consideration must be given to options that add flexibility such as flow contouring via adjustable blade angles (15% to 35%) and optimized gas flow patterns via baffling to avoid turbulence and excessive pressure drops. Even the availability and control of cooling water (capacity, temperature, and flow rate) must be carefully considered so as not to induce process variation as seasons change. With all of these factors in balance, the number of successful gear quenching applications is almost limitless.

Specification changes

Another change taking place is in the area of specifications. In order to help negate the influence of dimensional variation and to meet increased performance demands, the number and type of steps necessary in the processing of critical gear components are changing. An example of one proposed procedural specification is outlined below for AMS 6265 (aircraft quality AISI 9310) gears.

1 TECHNICAL REQUIREMENTS

1.1 Normalize, Reheat, Quench, and Temper: All parts shall be held at temperature for not less than one (1) hour per 25.4 mm (1 in.) of maximum cross sectional area in all operations. Normalize by heating to 954°C ± 5.5°C (1750°F ± 10°F) in a vacuum level of 1.3 mbar (1000 microns) maximum, and cool in nitrogen gas to simulate cooling in air. Without removing from the furnace, parts are then to be reheated to 815°C ± 5.5°C (1500°F ±10°F). Parts under 76.2 mm (3 in.) cross sectional area (maximum) are to be gas pressure quenched (20 bar minimum) using nitrogen gas. Parts of cross sectional area greater than 76.2 mm (3 in.) are to be quenched in highly agitated oil maintained in the range of 65°C – 88°C (150°F – 190°F). Double temper in a vacuum level of 1.3×10^{-3} mbar (1 micron) maximum at a temperature to produce a hardness of 270 – 300 BHN.

1.1.1 Hardness Measurement: Hardness shall be determined in accordance with ASTM E10.

1.1.2 Stress Relief: After machining and especially in cases where considerable stock removal has taken place, heat to 677°C ± 15°C (1250°F ± 25°F) and hold at temperature for not less than one (1) hour per 25.4 mm (1 in.) of maximum cross sectional area. Furnace cool to 371°C (700°F) then gas quench with nitrogen gas at 1– 2 bar pressure (maximum).to room temperature.

2. CARBURIZING

2.1 Cleaning: Parts shall be thoroughly cleaned by an approved degreasing method to remove oil, grease, and other surface contaminants that would otherwise inhibit diffusion of carbon through the surface boundary layer.

2.2 Masking. Selective carburizing may be accomplished by copper plating in accordance with AMS 2418 or by leaving surplus stock to be removed after carburizing. Stop off paint may be used when specifically authorized to do so.

2.3 Part Loading: Parts shall be suitably placed and supported in the carburizing basket to minimize distortion at temperature and to assure adequate circulation of the carburizing gas to all significant surfaces.

2.4 Carburizing: Carburize at 899°C – 954°C (1650°F – 1750°F) in a vacuum furnace for sufficient time to produce the required case depth and with sufficient gas flow to produce proper case microstructure and carbon gradation. The specified temperature shall be controlled within ± 5.5°C (± 10°F).

2.4.1 Carburizing for Limited Core Hardness: Carburize at 774°C – 871°C (1425°F – 1600°F) in a vacuum furnace for sufficient time to produce the required case depth and with sufficient gas flow to produce proper case microstructure and carbon gradation. The specified temperature shall be controlled within ± 5.5°C (±10°F).

2.4.2 Shallow Case Depth Carburizing: Parts having surfaces, such as splines, which are machined after carburizing and which require a shallow case depth not in excess of 0.25 mm (0.010 in.) may be heated in a vacuum furnace for sufficient time to produce the required case depth and with sufficient gas flow to produce proper case microstructure and carbon gradation on such surfaces.

2.5 Slow Cooling: When sufficient time has been allowed for the formation of the required case depth, slow cool by gas quenching with nitrogen gas at 1– 2 bar pressure (maximum) to room temperature.

2.6 Cleaning: Prior to hardening, parts shall be thoroughly cleaned by an approved degreasing method to remove oil, grease, and other surface contaminants.

2.7 Removal of Selective Carburizing Layer: If plated or painted for selected carburization, the removal of such materials should be in accordance with local, state, and federal regulations. Subsequent post carburization manufacturing processes can then be employed.

2.8 Hardening: Parts, prior to hardening, may be copper plated in accordance with AMS 2418 except that selective plating may be used provided that the hardening is performed in a vacuum or atmosphere neutral to the exposed case or core. Harden by heating to 802°C ± 15°C (1475°F ± 25°F), holding at the selected temperature for a minimal amount of time to soak the material. In general, this time should be less than thirty (30) minutes. Parts shall be properly supported, on fixtures if necessary, to prevent distortion and to permit uniform heating. Parts carburized for limited core hardness may be hardened by heating to 774°C – 802°C (1425°F – 1475°F).

2.9 Quenching. Parts may be quenched in a gas pressure quench (20 bar minimum) using nitrogen or in highly agitated oil maintained in the range of 65°C – 88°C (150°F – 190°F). Parts may be quenched in fixtures or presses to control distortion or in open baskets. In all cases the oil must circulate freely around every part. Allow parts to remain in the oil until the part temperature is below 93°C (200°F) followed by cooling in air to 38°C (100°F) or lower.

2.10 Cleaning: If oil quenched and prior to tempering, parts shall be thoroughly cleaned by an approved degreasing method to remove quench oil.

2.11 Tempering: Heat parts in a circulating air furnace to the indicated temperature holding at heat within ±5.5°C (± 10°F) for not less than one (1) hour per 25.4 mm (1 in.) of cross sectional area, and cool in air to room temperature. Double tempering is recommended.

As Tempered Hardness	Tempering Temperature
58 HRC minimum	177°C (350°F)
60 HRC minimum	149°C (300°F)

2.11.1 Re-temper: Parts initially tempered at 149°C (300°F) and exhibiting a hardness of 63 HRC or higher at the surface may subsequently be re-tempered by heating to a temperature not higher than 177°C (350°F), holding at heat for not less than one (1) hour per 25.4 mm (1 in.) of cross sectional area, and cool in air to room temperature.

2.12 Retained Austenite Conversion: When required to improve microstructure and minimize retained austenite after tempering, parts may be sub-zero cooled to a temperature not warmer than -101°C (-150°F) and held at this temperature or lower for a minimum of one (1) hour per 25.4 mm (1 in.) of cross sectional area but not less than thirty (30) minutes, and allowed to warm to room temperature in air on removal from the deep freeze.

2.13 Post Austenite Conversion Re-temper: Re-tempering parts by heating in a circulating air furnace within the range of 149°C – 177°C (300°F – 350°F), holding at the selected temperature within ± 5.5°C (±10°F) for not less than one (1) hour, and cool to room temperature in air.

2.14 Removal of Selective Carburizing Layer: If plated or painted for selected carburization, the removal of such materials should be in accordance with local, state, and federal regulations.

2.15 Stress Relief Temper: Applicable to all parts when grinding is performed, after hardening and tempering, particularly on carburized surfaces to provide final configurations and dimensions. Heat parts, either in a circulated air furnace, a vacuum furnace or in a suitable oil bath, within the range of 149°C – 177°C (300°F – 350°F) and hold at this selected temperature within ± 5.5°C (± 10°F) for two (2) to four (4) hours, and cool to room temperature.

GEAR HEAT TREATMENT TOMORROW

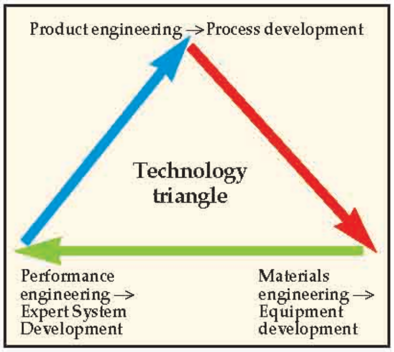

Fig. 6 — 21st century technology triangle.

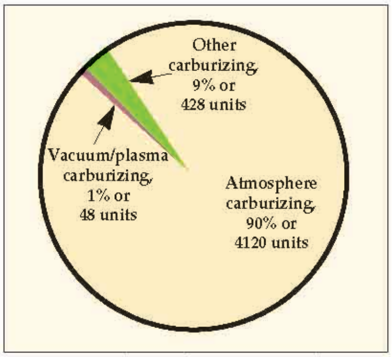

Fig. 7 — The North American carburizing market in 2000.

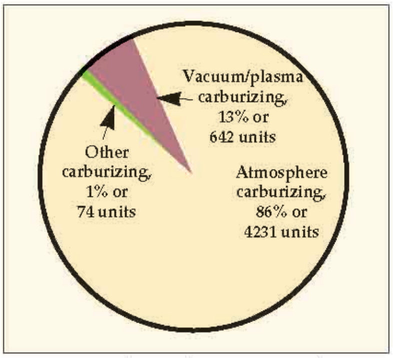

Fig. 8 — The North American carburizing market in 2010.

Tomorrow's gear industry is demanding higher power output from smaller, lighter, more versatile packages. This goal requires optimization of performance related issues, such as noise and weight reduction, dimensional control over geometry, and optimization of service life issues, such as bending and contact fatigue strengths and surface wear resistance. Reducing noise in spur gears, for instance, requires designs with a greater number of thinner teeth for higher contact ratios. As a result, heat treating processes that yield shallower case depths and high (0.90%) surface carbon levels are required.

The technology triangle (Fig. 6) tells us three things: product engineering is fueling process development (such as vacuum and induction carburizing); materials engineering is demanding new equipment development (via the creation of modular systems with decoupled efficiencies and total variable monitoring and control); and, performance engineering is giving rise to expert systems development (intelligent sensors and model driven simulators).

The North American carburizing market today (Fig. 7) is dominated by atmosphere carburizing equipment and will remain so tomorrow (Fig. 8). Yet the rapid developments in vacuum carburizing technology will continue to add a dramatic element to the industry in the near future.

Applications

Nothing illustrates the change taking place in the heat treating process selection area better than to look at a number of challenging gear applications where vacuum carburizing has been found process capable.

- *Automotive.* AISI 4820 sun gears (Fig. 9) are vacuum carburized at 930°C (1700°F) to an effective case depth of 0.75 to 0.90 mm (0.030 to 0.035 in.) and then pressure quenched at 12 bar using nitrogen. Load weight is 500 kg (1100 lb).

Made of powder metal (AISI 4142 equivalent), transmission gears (Fig. 10) having areas where the density is 7.75 g/cm^3 (0.28 lb/in.^{3}) are vacuum carburized at 880°C (1650°F) to an effective case depth of 0.36 mm (0.014 in.) and high pressure gas quenched using 12 to 15 bar nitrogen. As an alternative, these parts can be oil quenched. Load weight is 315 kg (700 lb).

- *Off-Highway.* AISI 8620 transmission gears (Fig. 11) are vacuum carburized at 980°C (1800°F) to an effective case depth of 1.15 to 1.65 mm (0.045 to 0.065 in.) and pressure quenched at 20 bar using nitrogen. Load weight is 430 kg (950 lb). As an alternative, these parts can be oil quenched and plug quenched.

AISI 9310 ring gears (Fig. 12) are vacuum carburized at 960°C (1750°F) to an effective case depth of 1.75 to 2.30 mm (0.070 to 0.090 in.) and pressure quenched at 11 bar using nitrogen. Load weight is 500 kg (1100 lb).

- *Heavy Truck.* AISI 8620 transmission gears (Fig. 13) are vacuum carburized at 960°C (1750°F) to an effective case depth of 1.15 to 1.65 mm (0.045 to 0.065 in.) and pressure quenched at 7 to 10 bar using nitrogen. Load weight is 160 kg (350 lb).

AISI 9310 pinions (Fig. 14) are vacuum carburized at 960°C (1750°F) to an effective case depth of 1.15 to 1.65 mm (0.045 to 0.065 in.) and pressure quenched at 7 to 10 bar using nitrogen. Load weight is 225 kg (500 lb).

- *Aerospace.* AISI 9310 transmission gears (Fig. 15) are vacuum carburized at 960°C (1750°F) to an effective case depth of 1.40 to 1.65 mm (0.055 to 0.065 in.) and pressure quenched at 6 bar using nitrogen. Load weight is 360 kg (790 lb).

Fig. 9 — AISI 4820 sun gears.

Engineered materials

Another driver in the gear technology of tomorrow will be in the area of engineered materials. In the past materials have been developed by empirical means, tomorrow they will be developed from a fundamental understanding of all aspects of material science. These design based materials will offer a broader range of performance but also demand new and different heat treatments.

Conclusions

The heat treatment of gears has entered a new era of rapid evolution. This bodes well for the future of the heat treatment industry as the revolution in materials development necessary to meet even more stringent performance demands is being met by equipment with extreme process flexibility. If heat treatment is to survive in the 21st century, it must be the most cost effective technology available. The changes now underway in the heat treatment industry will assure its continued growth and prosperity. **HTP**

Fig. 10 — Powder metal transmission gears.

Fig. 11 — AISI 8620 transmission gears.

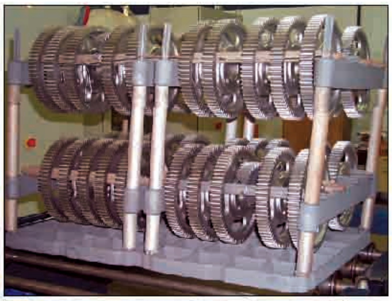

Fig. 13 — AISI 8620 timing gears.

Fig. 12 — AISI 9310 ring gears.

Fig. 14 — AISI 9310 pinions.

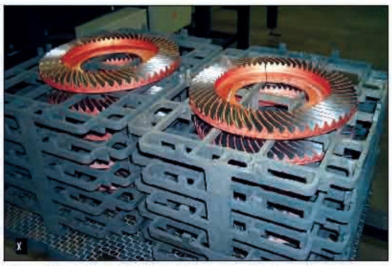

Fig. 15 — AISI 9310 transmission gears.

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