Gear Heat Treatment: The Influence of Materials and Geometry

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Management Summary

Gear designs are evolving at an ever accelerating rate, and gear manufacturers need to better understand how the choice of materials and heat treating methods can optimize mechanical properties, balance overall cost and extend service life.

This article focuses on these issues as well as presents an example from the automotive racing industry, where enhanced fatigue performance and reduced incidents of failure can be directly related to the design and control of materials, especially alloying element additions and selection of a complementary heat treatment process (low pressure/vacuum carburizing) with optimized process parameters.

Types of Gears

Gears play an essential role in the performance of the products that we rely on in our everyday lives. When we think about gears, we generally separate them into two categories: motion-carrying and power transmission. Motion-carrying gears are generally non-ferrous or plastics, while load bearing power transmission gears are usually manufactured from iron and steel. These gears (Fig. 1) are intended for heavy-duty service applications and will be the focus of the discussion that follows.

How Do Gears Fail?

The stresses that occur when the gears are in use and their surfaces in mesh must be carefully considered. To understand gear performance as it relates to materials (properties and heat treatment), the critical failure modes must be taken into account:

- Bending fatigue (root fillet cracks)
- Macropitting (pitch line surface degradation)
- Subcase fatigue (sub-surface fatigue failure)

Bending fatigue is caused by a load, applied along "the line of action," which generates stress gradients in the root fillets of the teeth. How these stress gradients react with the inherent strength gradients in part determines the fatigue life of the tooth (Ref. 1). The mode of failure tends to be in the form of crack propagation typically at the root fillet.

Macropitting can occur on the tooth surfaces, where the combination of pressure and sliding forces is the highest. Lubrication and surface finish can either promote or prevent macropitting. Where sliding is present and the coefficient of friction is high, the applied stress reaches a maximum at the surface and can exceed the material strength.

Subcase fatigue failure is another mechanism that can occur at the active profile face in that the applied stress level falls off gradually and can, therefore, approach or exceed the critical fatigue strength of the material. For case hardened parts, subcase fatigue usually occurs close to the case-core interface and cracking at the interface can be prevented by selecting, for a given material, the proper case depth and core hardness (that is, strength gradient) (Ref. 2).

Influence of Materials

Gears under load are subject to gradient stresses both on the active flank and at the root fillet. Properly selected materials and heat treatments will produce strength gradients that are adequate to withstand the stress gradients and provide an acceptable margin of safety.

In all gears, the choice of material must be made only after review of the performance demanded by the application. Material choice must be a balance between overall cost and required service life. Key design considerations require an analysis of the type of applied load, whether gradual or instantaneous, and the desired mechanical properties, such as bending fatigue strength or wear resistance. The required

Figure 1—Fire truck transmission gears. (Photograph courtesy of Twin Disc Inc.)

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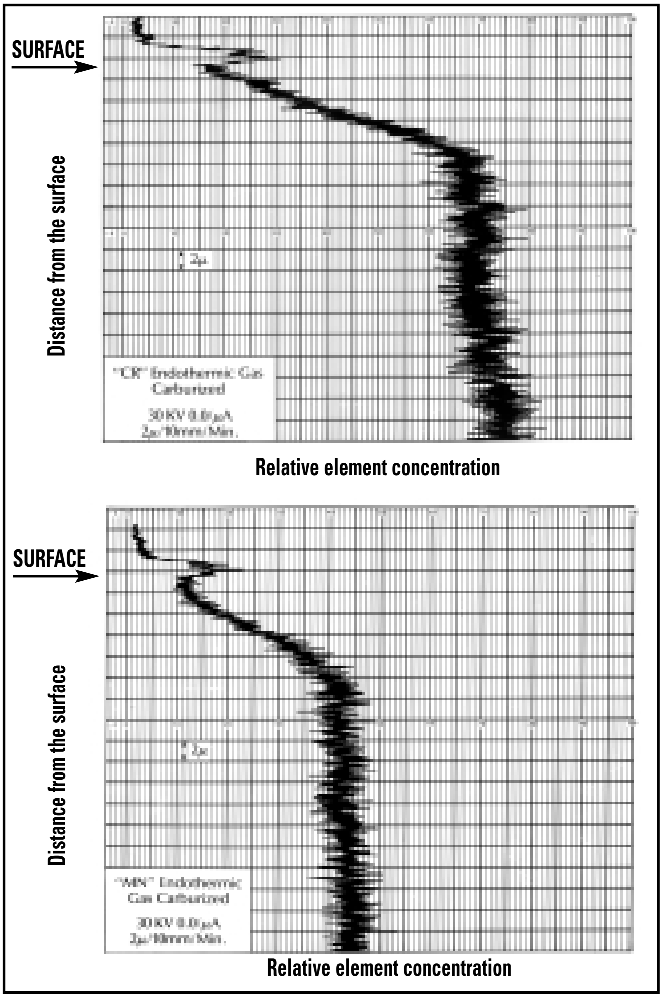


Figure 2—EDS analysis of atmosphere carburized gear surface oxidation effect for chromium (top) and manganese (bottom). Reading each scan from bottom to top, the specimen gear's surface is where the scan moves abruptly to the right.

Table 1—Available Gear Materials for Industrial Applications. (Ref. 3)

Typical Gear Materials (U.S. & European)	Gear Design Type	Typical Industrial Applications
(US) G3000, D5506, M5003, 1020, 1045, 1050, 1117, 1118, 1144, 4027, 4028, 4118, 4140, 4142, 4145, 4150, 4320, 4340, 4620, 4817, 4820, 5120, 5130, 5140, 5150, 8620, 8625, 8622, 8626, 8822, 9310 (European) 20NiCrMo2, 16MnCrB5, 20CrMo2, 17CrNiMo6, 20MoCr4, 18MnCrB5, 20CrMo4, 20MnCr5, 18NiCrMo5, 18MnCrMoB5, 27MnCr5, 27CrMo4, 23MnCrMo5	Face, Helical, Helical crossed-axis, Herringbone, Hypoid, Internal, Miter, Spiral/Straight Bevel, Skew Bevel, Spur, Spur rack and pinion, Worm, Zerol®	Differentials (automotive & heavy truck), Drives (industrial, tractor-accessory), Engines (heavy truck), Equipment (earth moving, farming, mining, paper/steel mill), Starters (automotive), Transmissions (aerospace, automotive, heavy truck, helicopter, marine, off-highway, tractor)

mechanical properties will define core strength and heat treating requirements. Manufacturing economics play an important role as well.

Each area in the gear tooth profile sees different service demands. For example, in the root area, good surface hardness and high residual compressive stress are desired to improve bending fatigue life. On the active flank, a combination of high hardness and adequate subsurface strength are necessary for adequate resistance to macropitting and subcase fatigue.

For example, some of the factors that influence fatigue strength are:

- Hardness Distribution
    - Case Hardness
    - Case Depth
    - Core Hardness
- Microstructure
    - Retained Austenite Percentage
    - Grain Size
    - Carbide Size, Type, and Distribution
    - Non-martensitic Phases
    - Intergranular Toughness
- Design and Manufacturing
    - Residual Compressive Stress
    - Surface Finish and Geometry

Although material cost represents only a small percentage (≈ 10%) of the total cost to manufacture a typical gear, material selection (Table 1) must be a perfect combination of raw material cost and performance capability.

Knowledge of the function of each of the alloying elements present in the material and their effect on the physical properties of the alloy is critical in material selection. Properties to be balanced by material selection include tensile, yield and impact strength, as well as elongation (Ref. 4).

Core Hardness. Core hardness is most strongly influenced by molybdenum and manganese. Chromium has a moderate effect and nickel a weak effect. Core hardenability is strongly influenced by quench temperature. For example, when quenching from 925ºC (1,700ºF) molybdenum has a notably stronger hardenability influence than any other element. Quenching from 830ºC (1,525ºF) reduces the effectiveness of molybdenum to a level that is more similar to the effect of manganese and chromium, with the effect of nickel remaining weak.

Susceptibility to bainite formation in the carburized case is strongly reduced by both molybdenum and chromium. Although manganese is the most cost effective element where core hardenability is concerned, high percentages of this element can create problems such as control of hardenability bandwidth (Ref. 5).

Surface Oxidation. Manganese and chromium are susceptible to oxidation in atmosphere carburizing, as is silicon (Ref. 6). Oxidation results in alloy depletion, which can be quantified by use of energy-dispersive X-ray spectroscopy (EDS). The technique separates and detects X-rays of specific energy levels that can be displayed as a line scan (Fig. 2) of relative element concentration (x-axis) as a function of distance from the surface (y-axis). In the case of manganese, the depletion results in lower hardenability and the formation of non-martensitic phases at the surface. Chromium loss contributes to difficulties with the formation of carbides in the case.

Shallow depths of surface oxidation appear to have no significant effect on fatigue properties, provided that the surface transforms to martensite (Ref. 7). Severe oxidation—which removes significant amounts of alloying elements from the austenite—lowers hardenability and allows other non-martensitic phases (pearlite and other decomposition products) to form. The formation of these phases reduces surface compressive stresses or results in surface tensile stresses and, therefore, is detrimental to fatigue (Ref. 8).

Influence of Part Geometry

Gear tooth profile, contact ratio, and pressure angle for a given application are critical in the proper selection of gearing for optimal use. The proper choice of heat treatment and surface treatment produce the strength and finish requirements necessary to perform the intended function.

Equally necessary to achieve high strength at the surface of the root fillet radius is a sound microstructure with material of high hardness.

Dimensional changes (growth, shrinkage, warpage) due to heat treatment cycle (heating and cooling) are a function of material selection, part geometry, manufacturing methods and equipment, and heat treatment process and cycles. Today, emphasis is placed on reducing the number of post heat treatment operations and, as such, heat treatment methods must be optimized.

Influence of Heat Treatment Method

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.

The greater the magnitude and depth of the 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.

Carburizing remains one of the most effective ways of producing beneficial compressive stress on the part surface. And of all the carburizing processes, low pressure/vacuum carburizing has emerged as the most effective (Ref. 9).

Low Pressure/Vacuum Carburizing. The development of carburizing steels specifically designed to take advantage of low pressure/vacuum carburizing methods in combination with high pressure gas quenching technology is one example of the promise of materials engineering for the future. The key to

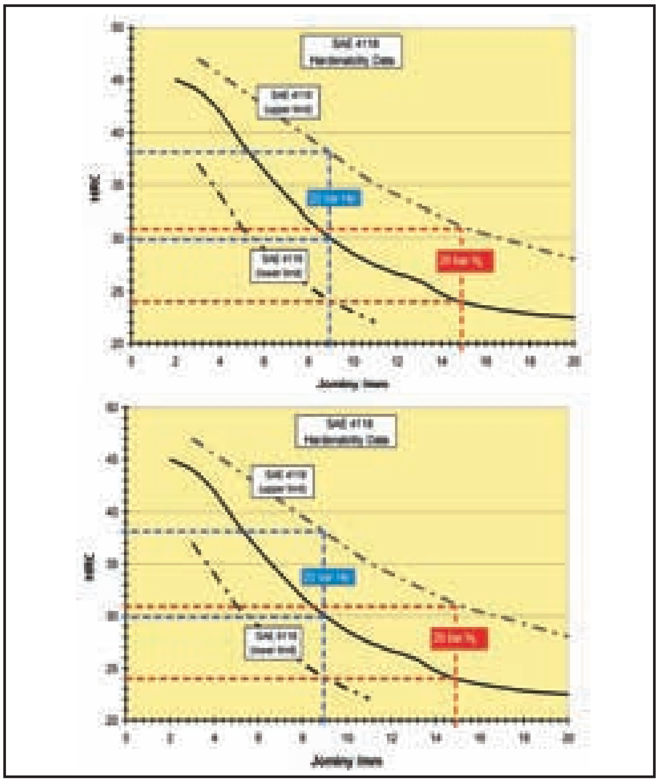


Figure 3—Influence of hardenability on gas quench properties.

Figure 4—Racing transmission gear (AISI 9310).

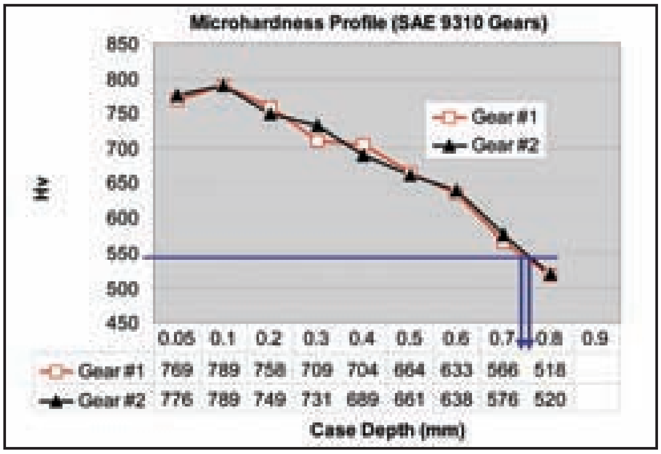


Figure 5—Gear effective case depth.

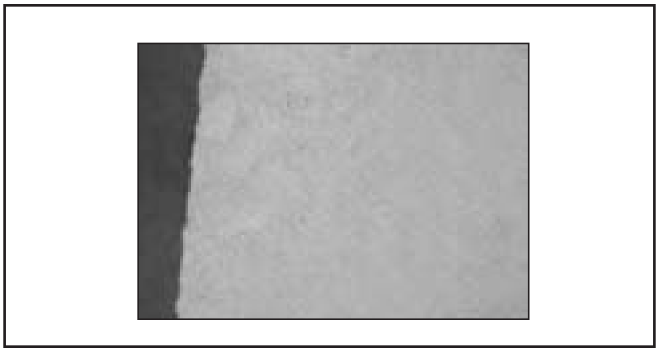


Figure 6—Gear microstructure (500X, 2% Nital)

Table 2—Gear Carburizing Requirements.

Items	Specifications
Part Description	Gear
Material	SAE 9310 Alloy Steel
Heat Treat Process	Carburizing
Effective Case Depth	0.025"–0.035" (0.63 mm–0.89 mm)
Carburized Surface Hardness	HRC 61.0 min.
Other Targets	No carbides, carbide networking or retained austenite
Quench	Nitrogen, 14 bar

Table 3—Shaft Carburizing Requirements.

Items	Specifications
Part Description	Main Shaft
Material	SAE 4820
Surface Condition	Clean (aqueous washing)
Heat Treat Process	Carburizing
Effective Case Depth	0.040"–0.050"
Carburized Surface Hardness	HRC 58–62
Other Targets	No carbides, carbide networking or retained austenite
Quench	Nitrogen, 18 bar

Figure 7—Racing transmission main shaft (AISI 4820).

these new steels will be their balance of material cost (targeting 10–25% of today's large quantity alloys) and performance (e.g. high hardenability and high toughness). In addition, using high pressure gas quenching to minimize part distortion reduces manufacturing cost. Considerable materials research is also underway to shorten cycle times by the use of high temperature carburizing methods. Micro-alloy additions of aluminum, niobium, and titanium have shown great promise (Ref. 10).

Other aspects, such as the tendency toward the formation of carbides and bainite in the case as discussed, must be taken into account. Generally speaking, low hardenability steels can be used for small gears, whereas higher hardenability is required for larger size gears. Since quench rate is also involved, there can be considerable variation. The more rapid the quench, the lower the hardenability required. However, where a particular heat of steel falls within its hardenability band is a factor that should not be ignored. For example, in high pressure gas quenching, this fact may dictate different types of quench gases and different gas pressures to achieve similar properties (Fig. 3).

A focus of this research has been to understand the effects of various alloying elements on core and case hardenability. Since base chemistry hardenability governs the capability of developing core and gradient strengths in the medium carbon portion of a carburized case and the lower carbon core region, understanding the relative magnitude of the major alloy element (manganese, nickel, chromium, and molybdenum) is very important. Case hardenability governs the capability of steel to develop sufficient hardness and microstructure in the high carbon surface. In general, performance life of carburized gears is dependent on surface microstructure, carbon content, strength gradient, residual stress and steel cleanliness (Ref. 11).

Racing transmission components (gears and shafts) can be used to illustrate the results that can be achieved by optimizing the heat treat process for a selected material (Ref. 12). These components are subjected to severe service duty and as such require the best achievable microstructure and properties.

Typical gears (Fig. 4) are processed as shown in Table 2.

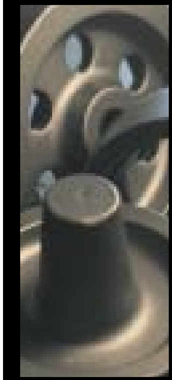
Checked gears showed uniform surface hardness that ranged from 64.2–64.7 HRC (as quenched). The effective case depth (Fig. 5) was measured as 0.75 mm (0.030") at 550 HV 0.5 (52.5 HRC). Carburized case microstructure (Fig. 6) revealed a uniform martensitic structure with no surface or intergranular oxidation, carbides, or retained austenite.

Main shafts (Fig. 7) in loads of 310 kg (690 lbs.) are processed to achieve the specifications called out in Table 3.

The shafts showed uniform surface hardness that ranged from 61.2–62.2 HRC after quench, deep freeze, and temper. The core hardness is 44.2–44.7 HRC. Parts were clean with a uniform total case depth of 1.32 mm (0.052") at 550 HV 0.5 (52.5 HRC).

Conclusion

Enhanced fatigue performance and reduced incidents of fail-



ures can be directly related to the design and control of materials, especially alloying element additions and the selection of a complementary heat treatment process with optimized cycle parameters to produce a fine martensitic microstructure in combination with a minimization or elimination of surface oxidation.

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