The Effect of Metallurgy on the Performance of Carburized Gears

Dr. Maurice Howes

Introduction

Gears are designed to be manufactured, processed and used without failure throughout the design life of the gear. One of INFAC's objectives (*see p.24) is to help manufacturers improve the manufacture of gears to optimize performance and life. One way to achieve this is to identify failure mechanisms and then devise strategies to overcome them by modifying the manufacturing parameters.

Over 20 modes of gear tooth failure have been identified by AGMA (Ref. 1), and they are often divided into the four broad headings of wear, pitting fatigue, plastic flow and tooth breakage. Nevertheless, Ku (Ref. 2) believed it was more logical to classify the gear-tooth failure modes under the two basic categories of strength-related modes and lubrication-related modes. However, this separation is not entirely possible and in practice many strength related failures are directly or indirectly influenced by lubrication.

From the INFAC perspective, it is assumed that the basic gear characteristics, including the lubrication, the loading and other running conditions, are decided by the gear designer. This article examines manufacturing parameters to determine how metallurgical and processing variables affect gear performance and to what extent gear life can be affected, even if only qualitatively. Most of the variables affecting performance are strength-related, although factors such as surface finish have an impact on lubricant film thickness and ultimately on the gear life.

The Need for Gear Life Performance Prediction

If gear life could be predicted, it would assist gear designers and manufacturers because:

1. Performance testing of gears is expensive and time-consuming.

2. A performance model would enable the interacting variables to be optimized.

3. An understanding of gear life factors would assist the gear designer in optimizing maufacturing cost and gear performance.

Processing with batch-type equipment always causes variation in metallurgical results from part to part. These manufacturing inconsistencies can directly impact performance. It is not sufficient to recognize the effects of processing on gear performance. The processing itself must be applied as consistently as possible to all parts if the gears are to perform in a similar manner.

Metallurgical Characteristics and Gear Performance

The metallurgical characteristics have a profound effect on performance, and the processing parameters must be carefully controlled. Even so, the ideal carburized case has possibly never been produced, but if it could be, it would probably be defined as one with a graduated carbon profile from the surface in towards the core without any surface effects such as decarburization, intergranular oxidation or carbides. The amount of retained austenite that would be tolerated would depend on the product and its use. The hardness at the surface would exceed HRC 60, and the residual stress levels would show a maximum compressive value very near the surface. However, these conditions are difficult to meet, and compromises are necessary to accommodate processing limitations. The following table summarizes metallurgical characteristics that must be considered that affect performance for three grades of gears, grade 3 being the highest, probably equivalent to a high grade aerospace gear. The three grades are intended to be comparable to those used in ANSI/AGMA 2001 and to have similar properties.

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<table>
<tr><th colspan="4">Effect of Metallurgical Characteristics on Gear Performance</th></tr>
<tr><th>Metallurgical Characteristic</th><th>Grade 1 Gear (least critical)</th><th>Grade 2 Gear</th><th>Grade 3 Gear (Highest)</th></tr>
<tr><td>Hardenability</td><td>Verification not required because the specified properties are easily attainable.</td><td colspan="2">Verification required to ensure hardenability is sufficient to produce the structures specified in later items. Alloy segregation is a non-homogeneous condition in the base material composition that is observed metallographically in the hardened microstructure when it is severe enough to affect hardenability and produce trace amounts of bainite. This condition is generally not cause for rejection by itself, but it can interact with other variables to produce an unacceptable metallurgical condition.</td></tr>
<tr><td>Nonmetallic Inclusions</td><td>Not specified because the required properties are easily attainable.</td><td colspan="2">It is necessary to control steel cleanliness and prevent inclusions causing unexpected failures in highly stressed areas. Consistent material with controlled levels of defects is essential to prevent unexpected life termination. A study of ISO standards and general European practice shows that even for the highest quality materials, such as VIM-VAR, occasional defects, which can initiate premature cracking, can be expected. If these defects do not break the surface, then they cannot be detected by magnetic particle testing. The recommended way to measure these defects is by ultrasonic inspection on the turned blank. The chances of such defects being present and being in a critical area are low, but when it does happen, a catastophic failure can be initiated.</td></tr>
<tr><td>Material Reduction Ratio</td><td>Not specified.</td><td colspan="2">Mechanical working is necessary to refine the structure and make it more homogeneous. Again we see the need for uniform structures and compositions.</td></tr>
<tr><td>Tempering After Surface Hardening</td><td>Recommended.</td><td colspan="2">Required for improved fracture toughness and stability. Also, if the part is not tempered above the working temperature, structural changes caused by heating in service will occur.</td></tr>
<tr><td>Surface Hardness on Tooth</td><td>55–64 HRC.</td><td colspan="2">58–64 HRC. Generally, resistance to pitting fatigue increases with surface hardness.</td></tr>
<tr><td>Effective Case Depth</td><td>Not specified.</td><td colspan="2">Minimum and maximum effective case depth depends on the rating standard (ANSI/AGMA 2004–B89). Optimum performance lies within this range.</td></tr>
<tr><td>Core Hardness</td><td>Not specified for pitting resistance. But 21 HRC minimum for bending fatigue.</td><td>21 HRC min. for pitting.
25 HRC min. for bending.</td><td>21 HRC min. for pitting.
30 HRC min. for bending.</td></tr>
<tr><td>Surface Carbon</td><td colspan="3">Fatigue strength and hardness increase with carbon content. The surface carbon content of a carburized gear will affect many of the metallurgical and fatigue characteristics that determine gear quality. The surface carbon has to be considered with alloy composition, quench characteristics, tempering conditions and numerous other heat treat cycle parameters used to produce a hardened gear. The process variables need to be controlled independently to make an acceptable part, but the alloy composition of the base material will dictate the surface carbon content range.
The following summarizes the surface carbon range as a function of alloy content for Grade 2 and Grade 3 gearing:
Broad band carbon range: 0.70% – 1.00.
Alloy Composition Range — Recommended Carbon Range
Up to 2.5% total alloy content — 0.80% – 1.00%
2.5% to 3.5% total alloy content — 0.75% – 0.95%
Over 3.5% total alloy content — 0.70% – 0.90%
These figures are for guidance only! Tighter tolerances are necessary for high quality parts.</td></tr>
<tr><td>Intergranular Oxidation</td><td colspan="3">This is detrimental to performance when complete networks are formed. Intergranular oxidation (IGO) is intrinsic in atmosphere carburizing furnaces. While the furnace atmosphere is controlled to protect the iron from oxidation, the water vapor and carbon dioxide components in endothermic atmospheres are still oxidizing to most of the alloying elements in the steel. The oxygen from these components is adsorbed at the surface and diffuses along the grain boundaries. As the oxygen diffuses along the grain boundary, it pulls alloying elements from the austenite grains and locally reduces the hardenability, which can have a detrimental effect on microstructure, mechanical properties and fatigue. It is this effect on microstructure that contributes to transformation products being present with IGO.
The depth of the intergranular oxidation is generally dependent on case depth, which is a function of the time at carburizing temperature; therefore, deeper case depths will have deeper intergranular oxidation depths. Vacuum carburizing treatments may reduce IGO.</td></tr>
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Continued on page 22.

Effect of Metallurgical Characteristics on Gear Performance (Continued)

<table>
<tr><th>Metallurgical Characteristic</th><th>Grade 1 Gear (least critical)</th><th>Grade 2 Gear</th><th>Grade 3 Gear (Highest)</th></tr>
<tr><td>Intergranular Oxidation (cont'd)</td><td colspan="3">For gearing applications intergranular oxidation is allowable to the following maximum limits:
<table>
<tr><th>Diametral Pitch</th><th>Grade 1</th><th>Grade 2</th><th>Grade 3</th></tr>
<tr><td>Fine to 6 DP</td><td>Not Specified</td><td>0.0007"</td><td>0.0005"</td></tr>
<tr><td>6 DP to 3 DP</td><td>Not Specified</td><td>0.0010"</td><td>0.0005"</td></tr>
<tr><td>3 DP to 2 DP</td><td>Not Specified</td><td>0.0015"</td><td>0.0008"</td></tr>
<tr><td>2 DP and larger</td><td>Not Specified</td><td>0.0020"</td><td>0.0010"</td></tr>
</table></td></tr>
<tr><td>Non-Martensitic Transformation Products</td><td>Not specified.</td><td colspan="2">Should be avoided.
Detrimental to performance.</td></tr>
<tr><td rowspan="2">Decarburization</td><td colspan="3">Detrimental to performance. Decarburization is the depletion of carbon on the surface. In carburized parts this usually occurs during reheating or during furnace temperature when the atmosphere carbon concentration is also changing, and the non-equilibrium condition at the part surface causes carbon to be depleted. The surface microstructure of a decarburized part may have a shallow depth of ferrite and/or bainite. The surface hardness may be reduced, depending on the severity of the decarburization condition.
Decarburization on the gear tooth surface will affect bending fatigue and pitting fatigue. The carbon composition change will modify the martensite reaction at the surface and tend to produce a more tensile residual stress at the surface, which will be detrimental to bending fatigue. The softer microstructure on the part surface will also affect the contact pitting fatigue. However, if the surface decarburization is not severe, the metal flow characteristics and the work hardening of the surface under load can combine to improve the load sharing and enhance the contact load carrying capability of the gear.</td></tr>
<tr><td>Does not have a decarburization specification, but the surface must meet the indention hardness specification.</td><td>Decarburization is not acceptable. Partial decarburization that is apparent at 500X is not acceptable, and the gear tooth surface must be Rockwell C58 and file hard.</td><td>Decarburization is not acceptable. Partial decarburization that is apparent at 500X is not acceptable, and the gear tooth surface must be Rockwell C60 and file hard.</td></tr>
<tr><td rowspan="3">Carbide Precipitation</td><td>Continuous networks are not permitted.</td><td>Discontinuous carbides are acceptable.</td><td>Dispersed carbides are acceptable.</td></tr>
<tr><td colspan="3">Carbide structures in the surface microstructure of case-hardened gearing are generally considered undesirable, and care in the heat treatment process must be taken to avoid carbide formation. The chemical composition of the base material will affect the tendency to form carbides. Chromium is the most common carbide forming alloying element used in steelmaking. Carbides are classified into three types: globular or massive carbides, network carbides and surface-film or flake carbides. Each type forms under different heat treatment conditions.
Globular or massive carbides form at the surface of a carburized part when the carbon concentration at the surface exceeds the equilibrium solubility limit. Controlling the atmosphere carbon concentration below the base material's solubility limit at carburizing temperatures will prevent the formation of massive carbides.
Massive carbides can also form during the initial heating process, when nascent carbon from the furnace atmosphere is more readily accepted and diffused into the austenite phase than the carbon from the existing carbide phase which developed during pretreatments. If an equilibrium condition is reached between the austenite and the carbide phases, the carbides will remain in the microstructure. Globular carbides can improve wear, abrasion and scuffing resistance; but they are detrimental to pitting resistance during gear mesh sliding.
Network carbides form during carburizing when the austenite phase is saturated with carbon above the eutectoid composition, and the excess carbon precipitates as carbides in the austenite grain boundaries. This can occur during the diffusion process and during quenching if the cooling rate is not sufficient to retain all of the carbon in the martensite-austenite structure. Network carbides are classified metallographically as continuous network, semi-continuous and discontinuous. The classification reflects the volume of grain boundary carbide present in the case microstructure. Surface-film or flake carbide is a continuous or discontinuous layer or film of carbide on the surface of the carburized case with little or no penetration below the surface. Generally this condition forms when the atmosphere carbon concentration is too high during cooling from carburizing temperature to quench temperature or during furnace cooling under protective atmosphere. This condition will give a high tensile surface stress condition. Under contact load the film will delaminate and give a crazed surface different from pitting. How this condition will affect contact fatigue is a function of the film thickness and the microstructure below the film.</td></tr>
<tr><td>Semi-continuous network carbides are permitted. Small, finely dispersed globular carbides are permitted in the case microstructure.</td><td>Discontinuous network carbides are permissible. Small, finely dispersed globular carbides are permissible on the surface to a depth of 0.003".</td><td>Only a light discontinuous network carbide with small, finely dispersed spheroidal carbides (that often precipitate during reheating) is permissible on the surface to a depth of 0.003".</td></tr>
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Metallurgical Characteristic	Grade 1 Gear (least critical)	Grade 2 Gear	Grade 3 Gear (Highest)
Retained Austenite	Performance increases with retained austenite until hardness starts to significantly decrease. The practical maximum is about 25%. Aerospace gears are generally subzero treated to transform austenite. This treatment has been reported by many references to cause microcracking and thus lower properties and result in a lower life. The INFAC cryogenic tests will be extended to look for the microcracking effect and assess the conditions under which it occurs. Retained austenite is present in most carburized gear case microstructures. Theoretically in carburized case conditions in excess of eutectoid carbon concentration, the martensite transformation reaction can never be complete, and some amount of austenite will remain at room temperature. Retained austenite is relatively soft, even though it is saturated with carbon. Retained austenite in a hard martensite microstructure will reduce the overall hardness of the structure. However, under load the retained austenite can transform to martensite, and it will strengthen the surface of the gear and improve its fatigue characteristics. Excessive amounts of retained austenite or light load conditions will not have this strengthening effect, and some control of the retained austenite content is required. Retained austenite concentration is difficult to measure metallographically; X-ray methods are recommended. The fatigue characteristics of the gear tooth surfaces are dependent on the material strength (hardness) and not usually correlated to the percent of retained austenite. Therefore, it is convenient to control/measure the retained austenite effects as they relate to hardness.		
	Retained austenite is acceptable, provided the gear tooth surface hardness is at least Rockwell C58. At this stress level there is no requirement for retained austenite concentration in the case microstructure.	Retained austenite is acceptable, provided the gear tooth surface hardness is at least Rockwell C58. At this stress level the retained austenite in the case microstructure should not exceed 30% measured metallographically.	Retained austenite is acceptable, provided the gear tooth surface hardness is at least Rockwell C60 (Rockwell 15N 90) and the microhardness at .005" depth is at least Rockwell C59 equivalent. The retained austenite in the case microstructure should not exceed 30% measured metallographically or 40% using X-ray diffraction techniques.
Microstructure of Core	Not specified.	A tempered martensite structure is preferred for maximim resistance to fatigue.	
Microcracks in Case	Microcracks are small cracks that may develop across or alongside high carbon martensite plates. The cracks are believed to be formed when the tip of a growing martensite plate impinges on another plate, cracking the impinged plate and/or the growing plate. There is little information on the influence of microcracks on material properties. However, it is reasonable to conclude that any cracking should be detrimental to material properties. Some controversy exists over the role of sample preparation in the incidence of microcracking. Certain researchers have shown that abusive sample preparation can precipitate microcracking. Also there is some speculation that the etchant may cause stress corrosion cracking of the martensite plates. Therefore, it is recommended that any specimen exhibiting microcracks should be repolished, lightly etched and observed immediately to confirm the existence of microcracks. A specimen shall be considered rejectable for microcracks under either of the following conditions: 1. Seven or more microcracks are visible in any field at 500X, 2. The longest microcrack in any field at 500X is 4 microns or longer.		
Bainite	Detrimental to performance, only trace amounts should be permitted. Bainite as a steel microstructure component is classified either as upper bainite, which is formed just below the pearlite reaction temperature, or lower bainite, which is formed closer to the martensite start temperature. Bainite, which is not a microstructural phase, but rather a mixture of ferrite and carbide, will etch dark in the microstructure. The microstructure appearance of upper bainite will be feathery, and lower bainite will be platelike (acicular) similar to martensite. It is normally assumed that: 1) Most bainite observed in carburized gear microstructures that propagates from the core into the case region is lower bainite formed during the quenching of the carburized gear, and 2) The bainite observed on the surface as a transformation product is upper bainite. Bainite formation from austenite is not athermal, but rather requires time for composition changes and diffusion of carbon. Increasing the rate of heat extraction from the gear tooth and/or increasing the material hardenability will retard the formation of bainite. In general the bainite reaction is not fully understood: however, bainite is not a desirable constituent in carburized gear microstructures. It does not have the high strength properties of martensite and can act as a nucleation site for pitting fatigue, very similar to inclusions in steel. Lower bainite that extends from the case to the gear tooth contact surface is not acceptable.		
	Trace amounts of bainite are acceptable, provided the bainite does not extendup to the surface of the gear tooth.	Gearing applications, trace amounts of bainite that are observable at 500X are acceptable in the gear root fillet area, provided it does not extend into the case region past the minimum effective case depth in the tooth contact area.	Lower bainite that is observable at 500X is not acceptable in the case microstructure in the contact area. In the root area, lower bainite is not acceptable in the first 20% of the case microstructure. Heavy pitch gearing may have special customer provisions.

Continued on page 24.

Effect of Metallurgical Characteristics on Gear Performance (Continued)			
Metallurgical Characteristic	**Grade 1 Gear (least critical)**	**Grade 2 Gear**	**Grade 3 Gear (Highest)**
Other Mixed Transformation Products	There are other microstructure considerations that can affect the carburizing heat treatment. These items are generally not permissible in Grade 3 gearing applications and should be reviewed for Grade 2 gearing applications. Transformation Products: These microstructure constituents are generally recognized as detrimental to the function of the gear. The transformation products, which occur along with intergranular oxidation, alloy inversion and decarburization, are usually associated with a localized loss in material hardenability. Generally bainite, ferrite and pearlite *are present in the transformation microstructure.* Generally trace amounts of transformation product observable at 500X on the tooth contact surface are acceptable in Grade 3 gearing applications. For Grade 2 gearing applications, some transformation product is permissible (5% at 500X) to a depth limit of half of the IGO depth specification. Grade 1 gearing generally will not have a specified requirement.		
Core Structure	Not specified.	Best performance obtained with tempered martensite. A trace of acicular ferrite and bainite is permitted, but blockly ferrite is not.	
Surface Cracks	Not permissible in functional areas.		
Surface Tempering or Burning	Not specified.	Burning or tempering is detrimental to performance and is not permissable, particularly in Grade 3 gear.	
Shot Peening	Not specified.	Enhances fatigue strength due to formation of residual stresses.	
Case Grain Size	A fine grain size is known to improve fatigue strength.		
Residual Stress Profile	Shot peening enhances fatigue resistance, but if not done by an automated method, it produces variable results.		
Case Carbon Profile	The case carbon profile may be changed by altering the parameters of a boost-diffuse cycle. It is believed that a flatter curve near the surface enhances fatigue resistance.		

Summary

Many of the characteristics in this table are connected, and gear performance can be maximized by controlling a few key factors listed below.

Material. The steel has to be uniform in composition, be without surface defects, and have adequate hardenability to produce martensitic structures in the size of gear being manufactured.

Carburizing. The treatment needs to be controlled to produce a uniform profile case, preferably in an atmosphere that excludes oxygen. Surface effects during carburizing must be minimized.

Hardening. The hardening process should not decarburize the steel, and the quench should be uniform, across the batch. A subzero treatment can be used, if necessary, to control austenite.

Grinding. The grinding process needs careful control to prevent surface overheating (burning) or tempering during aggressive metal removal. ○

References:

1. "Nomenclature of Gear Tooth Wear and Failure," AGMA Standard 110.03, 1962.
2. Ku, P. M. "Gear Failure Modes—Importance of Lubrication and Mechanics." ASLE Preprint No. 75AM-SA-1.

**Note: The Instrumented Factory for Gears (INFAC) is a U. S. Army Center of Excellence, and it is carrying out a program being conducted by the IIT Research Institute (IITRI) under the management and direction of the U. S. Army Aviation and Troop Command. The mission for INFAC is the development and application of technology to ensure an affordable, responsive and reliable U. S. gear production capability to meet current and future DoD requirements. The technology developed at INFAC is available to all U.S. industry, and requests for project listings and reports of completed programs may be made to IITRI at 312-567-4264.*