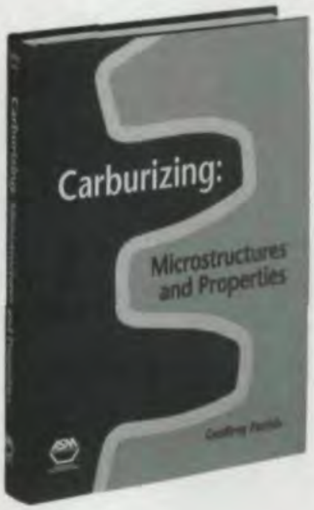
Geoffrey Parrish, *Carburizing: Microstructures and Properties*, 2nd ed., ASM, 1999, 247 pages.

Reviewed by Robert Errichello

Geoffrey Parrish has updated and expanded his previous book: *The Influence of Microstructure on the Properties of Case-Carburized Components*. It now contains at least twice the material. References and bibliography include 449 citations.

Carburizing should produce a tempered martensite surface. However, other microstructures may form. These can include internal oxidation, decarburization, free carbides, retained austenite, and microcracks. Parrish discusses these as well as microsegregation, cleanliness, grain size, and residual stress.



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is a technical editor for *Gear Technology*. He founded GEARTECH, a consulting company that specializes in gear failure analysis, in 1978. Many of their investigations have involved carburized gears.

Parrish explains how microstructural variations influence bending-fatigue strength, Hertzian-fatigue resistance, wear resistance, and scuffing resistance that are of particular interest to gear designers.

The following summarizes information provided by Parrish on the cause, effect, and remedy of adverse microstructural features.

Internal Oxidation

Cause. Conventional gas carburizing oxidizes elements in steel such as manganese, chromium, titanium, silicon, and aluminum, but not iron, tungsten, molybdenum, nickel, or copper. Oxidation mainly occurs along the grain boundaries at the component's surface and penetrates to a depth of on me or two grains. The elements involved diffuse to form the oxides and consequently an alloy-depleted surface layer with low hardenability.

Effect. Since most carburized gears are ground, internal oxidation is removed from active flanks, and does not affect surface properties such as Hertzian-fatigue resistance or scuffing resistance. Internal oxidation is of most concern for its effect on the properties of unground tooth root fillets. On their own, these oxides are not thought to be particularly detrimental. However, any nonmartensitic microstructures (pearlite, Bainite) that forms due to local alloy depletion are detrimental because they:

- Reduced near-surface hardness.
- Lead to tensile residual stresses.
- Reduced bending-fatigue resistance up to 35%.

Remedy. Internal oxidation can be eliminated by using oxygen-free carburizing atmospheres or vacuum-carburizing processes. With conventional gas carburizing, the effects of internal oxidation can be mitigated through steel design, process control, mechanical or chemical removal, and gear design. The steel alloy should contain:

- Carbon for adequate core strength, but not enough to reduce compressive residual stress or cause excessive distortion or growth.
- Nickel to add toughness to case and core, and suppress HTTP.
- Molybdenum to increase hardenability of case and core, and suppress HTTP.
- Manganese and chromium to enhance hardenability, but less than 0.5% of each.

Process control measures include:

- Prior to carburizing, ensure surfaces are free of scale, rust, or lubricants.
- Use vigorous quenches to minimize HTTP.
- Introduce ammonia into carburizing chamber for a short period at end of carburizing cycle.
- Use nitrogen-based or exothermic-based atmospheres.

Oxides and HTTP can be removed by electropolishing, electrochemical machining, honing, grinding, grit blasting, shot blasting and shot peening. Some of these methods risk negative side effects. For example, abusive grinding can induce tensile residual stresses and reduce bending-fatigue strength significantly.

Finally, engineers can reduce the significance of internal oxidation by designing gears with low bending stresses.

Decarburization

Cause. Decarburization, carbon loss from the workpiece surface, occurs above 700°C when the furnace atmosphere contains decarburizing agents such as carbon dioxide, water vapor, hydrogen, and oxygen.

Effect. Shallow decarburization, a minor reduction of surface carbon, does not greatly influence macrohardness. Severe decarburization results in ferritic or bainitic surface microstructures that significantly reduce hardness and fatigue strength.

Remedy. Severe decarburization rarely occurs with modern atmosphere monitoring systems, good plant maintenance and supervision, and sound process control. Decarburization that is caused by inadequate diffusion time or incorrect atmosphere during the boost/diffuse cycle is easy to correct. Parts with shallow decarburization may be salvaged by grit blasting to remove the affected layer and shot peening to ensure compressive residual stresses. For deeper decarburization, consider restoration carburizing if added distortion can be tolerated.

Carbides

Cause. The amount of carbide and its morphology depend on carbon content, alloy content, and cooling rate. Carbides form at the carburizing temperature if the carbon content of the austenite exceeds the Acm carbon level. If austenite contains carbon in excess of the eutectoid composition, but less than the Acm carbon level, carbide will precipitate at the austenite grain boundaries (networks) during slow cooling from carburizing. Formation of network carbides indicates that the carbon potential was too high for the steel concerned. The elements promoting carbide formation are phosphorus, which segregates to grain boundaries, and chromium that forms spheroidal carbides. The elements that suppress carbide formation are silicon, nickel, and molybdenum. Since carbides develop during slow cooling from carburizing and reheat quenching, direct or single quenching tends to suppress carbide development.

Effect. Fine, dispersed carbide particles are not regarded as detrimental. However, massive globular and network carbides reduce bending-fatigue resistance. Above 30% carbide content, fracture toughness progressively declines.

Remedy. Methods to prevent carbides include:

- Avoid excessively high carbon potentials.
- Round edges of workpiece to deter carbon buildup.
- Use fine grain steel to reduce the amount of carbon deposited at grain boundaries.
- Avoid steel alloys prone to developing network carbides such as lean-alloy grades with high chromium or manganese content.
- Consider subcritical annealing and requenching to modify (spheroidize) carbides. A high reheat temperature is feasible, but might create other problems such as grain growth, retained austenite, and distortion.

Retained Austenite

Cause. If part of the martensite transformation range lies below the quenchant temperature, some austenite will be retained. The amount depends on the steel alloy, carbon content, quenching temperature, and quenchant temperature.

Effect. Retained austenite reduces hardness, strength, and compressive residual stress. It is detrimental to both bending fatigue strength and scuffing resistance. If excessive, retained austenite may promote grinding cracks.

Remedy. Carbon potential and quenching temperature must be appropriate for the steel alloy. Lean alloys are usually direct quenched, and highly alloyed steels are usually reheated and quenched. Quenchant temperature must be low enough to avoid excessive retained austenite. Refrigeration reduces retained austenite and raises surface hardness, but it can reduce bending fatigue strength.

Grain Size

Cause. Grain size is refined by adding elements such as aluminum and vanadium to molten steel. Grain size is influenced by the austenitizing temperature and soak time, where high temperature and long soak times prior to quenching can encourage grain growth.

Effect. Fine grains developed after heat treatment improve most properties including fatigue strength and fracture toughness. Coarse-grained steels distort more during heat treatment and are prone to cracking and microcracking during quenching or grinding. An inherently fine grained steel can make quench hardening difficult.

Remedy. Purchase steel with appropriate quality and test grain size to ensure it is within ASTM No. 5 to 8. Normalize forgings and bar stock.

Microcracking

Cause. Microcracks form when growing martensite plates collide severely. The risk increases when the carbon content is above 0.8%. Steels with carbide forming elements are susceptible to microcracking, especially if grains are coarse.

Effect. Experiments are not conclusive, but it is possible that severe microcracking will have an adverse effect on bending fatigue strength.

Remedy. Use fine-grained steels and avoid lean-alloy steels. Limit surface carbon content. Direct quenching appears to produce more microcracks than does reheat quenching. Tempering immediately after quenchin drives off hydrogen and thereby removes a potential contributor to microcracking tendency. Do not refrigerate.

Microsegregation

Cause. Microsegregation occurs as steel solidifies in ingot molds. Alloying elements segregate as dendrites grow. The order of susceptibility (most prone to least) is sulfur, niobium, phosphorus, tin, arsenic, molybdenum, chromium, silicon, manganese, and nickel. Forging distributes microsegregation into bands.

Effect. Hardenability of alloy-rich bands is higher than alloy-lean bands. Bainite or other HTTP may form in alloy-lean bands resulting in low fatigue strength and failure if HTTP occurs in highly stressed areas.

Remedy. Microsegregation cannot be avoided. However, adequate mechanical working during forging helps to redistribute segregation to more favorable directions. Soaking at elevated temperature can reduce microsegregation, but soak times can be lengthy.

Nonmetallic Inclusions

Cause. All steels contain numerous nonmetallic inclusions, but cleaner grades have fewer large inclusions. In clean steel, most inclusions are less than 0.2 μm, whereas dirty steel contains many inclusions larger than 20 μm. Some inclusions are introduced in molten steel when refractory material separates from furnace linings, runners, and ladles. Other inclusions form because of reactions during deoxidation in the melt or during solidification.

Effect. Many fatigue cracks initiate at nonmetallic inclusions. Harmful effects depend on chemistry, size, location, and quantity of inclusions; strength of the steel; and residual stresses immediately adjacent to inclusions. Many fatigue failures are initiated at inclusions located near the case/core boundary, where residual stresses are tensile. Hard, undeformable inclusions such as calcium aluminates, alumina, spinels, titanium nitride, and silicates are most damaging and mangananese sulfide is regarded as being the least potent.

Remedy. Control steel cleanliness by using modern steelmaking processes such as vacuum degassing, electroslag remelting, or vacuum-arc remelting.

As you can see from the above, Parrish discusses many important microstructural features of carburized components. However, the book covers much more including core properties and case depth, postcarburizing thermal treatments (tempering and refrigeration) and postcarburizing mechanical treatments (grinding, roller burnishing, and shot peening).

Failure analyses show carburized gears often fail because of defective metallurgy. This is not surprising, given the number of variables involved, and the tight controls required for manufacturing high quality gears. More often than not, Parrish's previous book explained why these failures occurred. Now, *Carburizing* promises to be even more helpful.

Parrish's text is a valuable resource for gear engineers, heat treaters, quality assurance personnel, and failure analysts. My confidence in a gear manufacturer will be heightened if the heat treater has a dog-eared copy of *Carburizing*. ○

To order *Carburizing: Microstructures and Properties*, call ASM at (440) 338-5151.

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