

Title Case Study 2: Surface Hardening of Steel Gears

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Case Overview

The gears in a car's transmission must be incredibly durable. The surface of the gear teeth needs to be extremely hard to resist wear from constant contact, but the core of the gear needs to be tough and ductile to absorb shock and prevent shattering. These conflicting property requirements are achieved through surface hardening.

Key Questions to Investigate:

- What is carburizing? How does this process use the principles of diffusion to change the composition of the steel's surface?
- Using the iron-carbon phase diagram, explain the phase transformations that occur at the surface during the subsequent heat treatment (quenching and tempering) to create a hard case.
- Why is the core of the gear not affected in the same way? How does its microstructure differ from the case?
- Compare carburizing with another surface hardening technique, like nitriding or induction hardening.

Relevant Course Concepts:

- Diffusion Phenomena: The fundamental process behind moving carbon atoms into the steel.
- Fick's Law: The law that governs the rate of this diffusion.
- Factors that Affect Diffusion: Specifically, the critical role of temperature.
- Iron-Carbon Phase Diagram: Essential for understanding the heat treatment process that follows carburizing.
- Phase Transformations in Steels: The formation of hard martensite at the surface.

My Analysis

Introduction

The gears within an automotive transmission operate under extreme conditions, requiring a unique and seemingly contradictory combination of material properties. The gear teeth surfaces must be exceptionally hard and wear-resistant to withstand the constant friction and contact stresses of meshing. Simultaneously, the core of the gear must be tough and ductile to absorb shock loads and prevent brittle fracture. Fulfilling these conflicting requirements in a single monolithic component is a classic challenge in materials engineering. The solution lies not in a uniform material, but in creating a composite-like structure through surface hardening. Carburizing, a thermochemical diffusion process, is a primary method used to achieve this, selectively modifying the surface of the steel to produce a hard case while maintaining a tough core.

The Carburizing Process: A Diffusion-Based Approach

Carburizing is a surface-hardening technique that fundamentally alters the chemical composition of a steel component's surface. The process leverages the principles of atomic diffusion, a phenomenon governed by Fick's Laws. To begin, a low-carbon steel gear (typically with 0.1% to 0.25% carbon) is placed in a sealed furnace and heated to a high temperature, usually between 900°C and 950°C. At this temperature, the steel transforms into the austenite phase, which has a face-centered cubic (FCC) crystal structure. The FCC structure has larger interstitial sites than the room-temperature body-centered cubic (BCC) structure, allowing it to dissolve a significantly higher amount of carbon.

Once the gear is at temperature and fully austenitic, a carbon-rich atmosphere (using gases like methane or carbon monoxide) is introduced into the furnace. This creates a high concentration of carbon at the surface of the gear and a low concentration in its interior. This concentration gradient is the driving force for diffusion. Carbon atoms from the atmosphere are adsorbed onto the steel's surface and then diffuse interstitially, moving from one empty site to another within the austenite crystal lattice, from the high-concentration surface into the low-concentration core. The rate of this diffusion is critically dependent on temperature; the high heat provides the necessary thermal energy for the carbon atoms to overcome the activation energy barrier for movement, a relationship described by the Arrhenius equation. This process continues for a calculated period, allowing a controlled depth of carbon enrichment, known as the "case depth."

Phase Transformations and Microstructural Control

Following the carburizing stage, the gear possesses a dual nature: a high-carbon surface (the "case") and a low-carbon interior (the "core"). To develop the final desired properties, the gear undergoes a precise heat treatment process, the effects of which are best understood using the Iron-Carbon phase diagram.

First is the quenching. Immediately after carburizing or after a re-heating step, the entire gear is rapidly cooled, or quenched, typically in oil. For the high-carbon case (e.g., 0.8% C), this rapid cooling prevents the normal equilibrium transformation from austenite to pearlite. Instead, the austenite transforms into martensite, a body-centered tetragonal (BCT) metastable phase. The BCT structure is formed because the high concentration of carbon atoms does not have time to diffuse out of the crystal lattice and becomes trapped, distorting the structure and creating immense internal strain. This strain is what makes martensite extremely hard and brittle.

Second is the tempering. Because the as-quenched martensitic case is too brittle for most applications, the gear is subjected to a tempering process. This involves reheating the gear to a much lower temperature (e.g., 150°C to 200°C) and holding it for a specific time. This treatment allows a small amount of carbon to precipitate out as fine carbides, which slightly relieves the internal stresses of the martensite. The result is a significant increase in toughness and ductility with only a minor reduction in the high hardness of the case.

The Duality of Core and Case

The core of the gear is not affected by the heat treatment in the same way as the case, precisely because of its low carbon content. Although the core is also heated to the austenite phase and quenched, its low carbon concentration is insufficient to form a fully martensitic structure. Instead, upon quenching, the core transforms into a much softer and tougher microstructure, often a mix of low-carbon martensite, bainite, and/or fine ferrite and pearlite. This microstructure provides the necessary ductility and toughness to absorb impacts and resist the propagation of any cracks that might form on the surface, preventing the gear from shattering under load. The final product is therefore a component with a hard, wear-resistant surface (tempered martensite) and a tough, shock-absorbent core (ferrite/pearlite/bainite).

Comparison with Induction Hardening

Carburizing can be contrasted with another common surface hardening technique called "induction hardening". Unlike the thermochemical process of carburizing, induction hardening does not alter the chemical composition of the steel. Instead, it is a thermal process that requires a steel with sufficient initial carbon content (typically medium-carbon steel, 0.4% to 0.6% C) to achieve high hardness.

In induction hardening, a high-frequency alternating current is passed through a copper coil placed around the gear tooth. This induces eddy currents in the surface of the steel, rapidly heating it into the austenite range in a matter of seconds. The heating is localized to the surface; the core remains cool. The part is then immediately quenched. Because only the surface was heated to form austenite, only the surface transforms into hard martensite upon quenching.

Most significant differences are as follows:

- Mechanism. Carburizing is a chemical process (adding carbon), while induction hardening is a thermal process (selective heating).
- Material. Carburizing uses low-carbon steel, while induction hardening requires medium-carbon steel.
- Process time. Carburizing is a slow, time-consuming process (hours), whereas induction hardening is extremely fast (seconds).
- Distortion. The prolonged high heat of carburizing can cause more component distortion than the rapid, localized heating of induction.
- Geometry. Carburizing is effective for complex shapes, while induction hardening is best suited for more regular geometries where a coil can be placed effectively.

Conclusion

A transmission gear is a good example of the core principle of materials science. Altering a material's microstructure to achieve specific, and often conflicting, performance properties are what these engineers in this field do. The carburizing process is a sophisticated application of diffusion and phase transformation principles. By creating a controlled carbon concentration gradient, engineers can subsequently use heat treatment to generate two distinct microstructures, a hard, wear-resistant martensitic case and a tough, ductile core, within a single steel component.