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"INFLUENCE OF AUSTEMPERING AND MARTEMPERING ON THE MICROSTRUCTURE AND MECHANICAL PROPERTIES OF HIGH-CARBON BEARING STEELS: A REVIEW"

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ABSTRACT

High-carbon bearing steels, such as EN 100Cr6, AISI 52100, and EN 100CrMo7, are the backbone of rotating machinery where extreme hardness, excellent compressive strength, and high rolling contact fatigue (RCF) life are critical prerequisites. Traditionally, these alloys undergo conventional through-hardening and tempering to establish a hard martensitic matrix. However, severe oil quenching introduces aggressive thermal gradients, significant internal residual stresses, and dimensional distortions. To mitigate these processing defects, interrupted quenching routines—specifically austempering and martempering—are widely utilized. This review synthesizes the current literature regarding the effects of austempering and martempering parameters on the microstructural evolution and mechanical properties of bearing steels. Martempering paths, executed by quenching the material slightly above its martensite start temperature (M_s) prior to calm air cooling, maximize hardness (up to 66 HRC) and dry sliding wear resistance through an ultra-hard matrix of untempered tetragonal martensite, primary carbides, and significant retained austenite (RA). Conversely, austempering involves holding the material isothermally within the bainitic transformation window (typically 200°C to 300°C) to yield a nano/ultrafine lower bainitic ferrite matrix bound by thin, carbon-stabilized films of retained austenite. This bainitic architecture significantly elevates impact toughness, fracture resistance, and dimensional stability under severe cyclic fatigue. This paper systematically reviews how key processing boundaries (e.g., austenitizing temperatures, isothermal salt bath durations, and tempering conditions) govern the volume fractions, morphologies, and operational behaviors of these competing phases to optimize heavy-duty structural bearing components.

Key Words: *Bearing Steel, Austempering, Martempering, Retained Austenite, Bainite, Martensite, Rolling Contact Fatigue.*

I. INTRODUCTION

Industrial bearing components function under intense cyclic contact pressures and must maintain pristine surface finishes to avert premature failure. High-carbon hypereutectoid alloys, such as EN 100Cr6, AISI 52100, and EN 100CrMo7, are universally favored for rolling elements due to their unique capacity to balance load-bearing rigidity with high abrasion resistance (Fortini et al., 2024; Matteis, 2025; Toktaş et al., 2018). Traditionally, these materials are through-hardened by austenitizing, directly quenching in oil, and performing low-temperature tempering (Fortini, 2023). However, rapid direct quenching creates severe non-uniform heat transfer, establishing a steep thermal gradient between the component's exterior surface and inner core (Fortini, 2023). This thermal mismatch induces substantial internal stresses and macroscopic distortions, necessitating expensive post-hardening grinding stages or even causing catastrophic quench cracking (Fortini, 2023).

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To bypass these manufacturing challenges, industrial protocols leverage interrupted thermal routes: **martempering** and **austempering** (Fortini et al., 2024). Both techniques use a molten salt bath to hold the components isothermally, allowing temperature stabilization across different cross-sections before structural transformation begins (Fortini et al., 2024). While both methods control dimensional distortion, they yield entirely different phase matrices and mechanical performance boundaries.

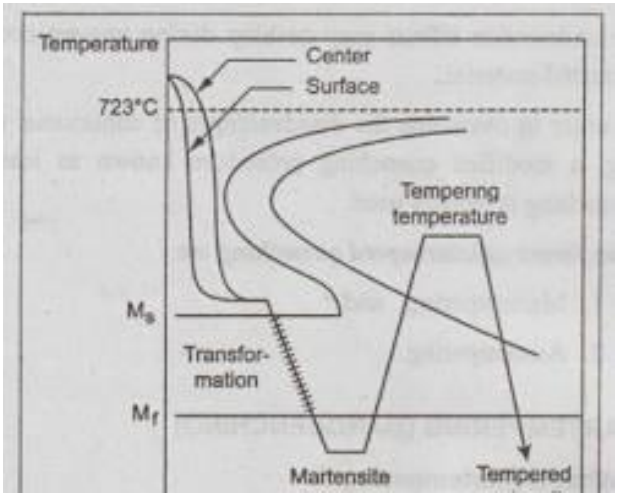

Figure.1 Thermal routes diagram

II. Process Mechanism and Microstructural Evolution

2.1 Martempering Microstructure

Industrial martempering is an interrupted quenching process optimized to limit transient thermal stress (Fortini et al., 2024). The steel is cooled rapidly from its single-phase austenite region into a salt bath kept just above the martensite start (M_s) boundary. It is held there long enough to achieve thermal equilibrium throughout the part's geometry without crossing into the bainitic transformation curve (Fortini et al., 2024). The component is then removed from the bath and allowed to cool slowly in air to room temperature.

The un-tempered microstructural outcome consists of:

- Highly acicular, carbon-supersaturated **tetragonal martensite** (Fortini et al., 2024; Matteis, 2025).
- Undissolved secondary **globular carbides** (primarily $(Fe,Cr)_3C$), which restrict prior austenite grain growth during high-temperature austenitizing (Fortini, 2023; Matteis, 2025).
- High initial volume fractions of **retained austenite (RA)**, which can reach up to 13.1 vol.% in the thick center zones of large-scale components prior to subsequent tempering steps (Fortini et al., 2024).

2.2 Austempering Microstructure

Unlike martempering, austempering involves complete isothermal transformation below the pearlite curve but within the bainitic transformation window—typically between 200°C and 400°C (Fortini et al., 2024). The steel remains immersed in the salt bath for an extended duration to allow the parent austenite to fully transform into lower bainite.

As bainitic ferrite plates grow, surplus carbon is continuously rejected into the adjacent, untransformed austenite zones (Matteis, 2025). This carbon enrichment strongly stabilizes the remaining parent phase, locally depressing its M_s temperature and allowing it to persist at room temperature (Matteis, 2025). Microscopic analysis reveals that this

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microstructure consists of nanoscale/ultrafine bainitic ferrite laths interspersed with retained austenite displaying two primary morphologies (Matteis, 2025; Solano-Alvarez et al., 2014):

1. **Fine interlath films:** Highly stable, carbon-dense regions that resist mechanical transformation.
2. **Micrometer-sized blocks:** Less stable pools located between adjacent bainite sheaves, which are vulnerable to transforming into brittle martensite under external stress (Solano-Alvarez et al., 2014).

III. Influence of Mechanical Properties

The diverging mechanical attributes achieved by these two heat treatment methods are compared below:

Table.1 Mechanical Properties

Property Metric	Martempering Regime	Austempering Regime
Peak Hardness	Exceptionally High ($\sim$63–66 HRC) (Fortini et al., 2024)	Moderate to High ($\sim$58–62 HRC) (Fortini, 2023)
Impact Toughness	Moderate; restricted by rigid martensite plates	Exceptionally Superior; resists shock loads (Fortini et al., 2024)
Retained Austenite (RA)	Higher initial vol.% (up to 13.1%) (Fortini et al., 2024)	Lower initial vol.% ($\sim$3.0–4.9%) (Fortini et al., 2024)
Dimensional Distortion	Low (controlled via thermal equilibrium) (Fortini et al., 2024)	Minimum (lowest volume expansion phase change) (Fortini, 2023)
Primary Wear Mode	Outstanding resistance to dry sliding abrasion (Fortini et al., 2024)	High rolling contact fatigue (RCF) life under impact

3.1 Hardness and Wear Behavior

Martempering yields a significantly harder matrix across the entire component profile than austempering routines (Fortini et al., 2024). For instance, in heavy-section EN 100CrMo7 rings, martempering routinely maintains a uniform hardness of up to 66 HRC across both surface and core tracks (Fortini et al., 2024). This structural rigidity effectively prevents plastic deformation, ensuring very low wear rates during dry sliding and abrasive friction tests (Fortini et al., 2024).

Austempering treatments inherently result in a lower peak hardness because bainitic ferrite holds less supersaturated carbon than tetragonal martensite (Matteis, 2025). Furthermore, the final hardness of austempered bearing steel depends strongly on the chosen salt bath temperature. Raising the bath temperature from 200°C toward 300°C coarsen the bainitic laths and lowers dislocation density, resulting in a progressive reduction in overall yield strength and hardness (Matteis, 2025; Wang et al., 2016).

3.2 Fracture Toughness and Fatigue Resistance

While martempering maximizes surface rigidity, austempering provides a superior balance of ductility, impact strength, and fracture resistance (Fortini et al., 2024; Matteis, 2025). The intricate, interlocking architecture of lower bainite plates acts as a highly effective energetic barrier, forcing propagating micro-cracks to continuously change directions.

Additionally, the stable, film-like retained austenite trapped between bainite laths functions as a localized plastic zone. These thin films accommodate micro-strains and arrest advancing cracks before they can cause catastrophic failure (Solano-Alvarez et al., 2014; Wang et al., 2016). Consequently, austempered elements provide highly resilient impact performance, which increases with longer isothermal soaking times until the bainitic transformation is complete (Fortini et al., 2024).

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IV. Retained Austenite Control and Dimensional Stability

Controlling retained austenite (RA) is an essential part of precision bearing engineering. While some RA can improve rolling contact fatigue performance via localized strain-induced plasticity, un-stabilized, metastable RA presents a major risk to long-term dimensional tolerances (Lindström, 2016). Over extended service lifetimes, under repetitive contact stresses or ambient temperature swings, un-stabilized RA can spontaneously transform into un-tempered martensite (Lindström,2016). This transformation causes localized volume expansion, which disrupts high-precision internal clearances and can trigger unexpected bearing binding or premature surface spalling (Fortini, 2023; Lindström, 2016).

The processing parameters directly dictate the initial volume fraction and spatial stability of the retained austenite phase: intrinsic stability

Austempering routines yield lower initial volume fractions of RA (ranging between 3.0% and 4.9%) than un-tempered martempered equivalents (Fortini et al., 2024). During subsequent tempering operations, both types of structures undergo further reduction in unstable phases. In martempered components, post-quench tempering lowers the core RA to roughly 2.0 vol.% (Fortini et al., 2024). However, the austempering route achieves a more complete and uniform stabilization, driving final RA values below 1.0 vol.% across both the surface and core of thick-section bearing rings (Fortini et al., 2024). This high dimensional stability makes austempering the preferred choice for high-precision, long-life industrial bearing applications.

V. Conclusion

This review highlights the microstructural changes and mechanical trade-offs that occur when applying austempering and martempering to high-carbon bearing steels:

1. **Martempering** successfully minimizes severe quenching distortions while producing a uniform, highly rigid matrix dominated by acicular tetragonal martensite and primary carbides. It achieves outstanding peak hardness ($\sim$63–66 HRC) that excels in severe dry sliding wear environments.
2. **Austempering** generates a nanoscale or ultrafine lower bainite structure interwoven with carbon-stabilized retained austenite films. This unique arrangement provides superior impact toughness, high fracture resistance, and excellent performance in environments subject to shock loading.
3. **Dimensional stability** is optimized through austempering, which limits the final retained austenite volume fraction to less than 1.0 vol.% post-tempering. This effectively eliminates the risk of late-stage strain-induced structural expansion during high-stress operations.

Ultimately, selecting between these two modified heat treatments requires balancing the specific demands of the application: martempering is preferred for maximum surface hardness and wear resistance, while austempering is selected for environments subject to high impact and requiring strict dimensional stability.

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