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Review on Microstructure and Properties of 45 Steel under High-Temperature Tempering

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Abstract

As the most widely used medium-carbon structural steel in the machinery manufacturing industry, 45 steel exhibits service performance of components that is decisively governed by the selection of process parameters for high-temperature tempering. This paper summarizes the microstructural evolution and mechanical properties of the aforementioned two materials under high-temperature tempering conditions. For 45 steel, research findings and mainstream conclusions from existing literature are elaborated from five perspectives: heat treatment surface effects, fatigue behavior regulation, high-temperature mechanical characteristics, innovative process exploration, and hardness degradation laws.

Keywords

45 Steel; High-Temperature Tempering; Microstructure Stability

Introduction

45 steel is categorized as high-quality carbon structural steel with a carbon mass fraction ranging from 0.42% to 0.50%. Benefiting from abundant raw material supply, excellent machinability and moderate cost, it is extensively adopted to fabricate fundamental mechanical components such as shafts, gears, connecting rods and fasteners. In recent years, domestic researchers have carried out extensive experimental investigations and theoretical analyses focusing on the high-temperature tempering of 45 steel. The research covers multiple aspects, including the correlation between process parameters and macroscopic mechanical properties, thermodynamic and kinetic mechanisms governing microstructural evolution, carbide precipitation modes, as well as segregation behaviors at grain boundaries.

1. Research Progress on High-Temperature Tempering of 45 Steel

Owing to its relatively simple alloy system, 45 steel has been extensively investigated with a broad research scope. Relevant studies not only cover the optimization and screening of conventional process parameters, but also include intervention strategies targeting specific failure modes and feasibility verification of novel process routes. The existing literature is sorted out below according to different research emphases.

1.1. Effect of Heat Treatment on Surface Integrity

Hao Shaoxiang et al. [1] investigated the influence law of heat treatment processes on the surface roughness of 45 steel components. By comparing the surface conditions of specimens treated under various quenching heating atmospheres and cooling conditions, they revealed the non-uniform distribution of hardness gradients induced by high-temperature oxidation and surface decarburization. When blanks with surface defects proceed to the finishing process, periodic fluctuations occur in cutting force, which ultimately degrade the quality of machined surfaces.

1.2. Effect of Process Parameters on Fatigue Life

Taking 40Cr steel as the experimental material, Yang Xiaohua and Wu Weiqing [2] explored the effect of an intermediate high-temperature tempering procedure on material fatigue life. Their research ideas provide reference value for the heat treatment process design of 45 steel. Experimental results indicate that suspending the fatigue test after a certain proportion of fatigue loading cycles and subjecting specimens to supplementary high-temperature tempering leads to non-monotonic variation in the residual fatigue life. The researchers attributed this phenomenon to the redistribution of internal microzone residual stress fields and the irreversible evolution of dislocation configurations during tempering.

1.3. Mechanical Behavior Characteristics at High Temperature Range

Sun Yanhui et al. [3] conducted systematic high-temperature tensile tests on medium carbon steels including 45 steel via thermal simulation experiments. Continuous curves describing the variation of reduction of area and ultimate tensile strength of 45 steel were obtained within the temperature range from 700 °C to the solidus temperature, and two characteristic temperature zones with drastically deteriorated plasticity were identified. The research reveals that the first brittle temperature zone is closely associated with residual liquid films distributed between dendrites, while the third brittle temperature zone is primarily induced by the non-equilibrium precipitation of sulfides, carbonitrides at austenite grain boundaries. The research findings provide definite process boundary conditions for establishing heating specifications of large-sized 45 steel forgings and avoiding plastic deformation or straightening operations within the temperature zones of low plasticity.

1.4. Investigation on the Mechanism of Abnormal Grain Growth

In his doctoral dissertation, Huang Jian [4] took carburizing steel for gears as the research object and carried out targeted research on the abnormal grain coarsening occurring during high-temperature treatment. The experimental results demonstrate that once the heating temperature exceeds a certain critical threshold, individual giant grains with sizes far larger than the average value abruptly emerge among the initially uniform and fine austenite grains, and this phenomenon presents obvious abrupt and irreversible characteristics. Combined with thermodynamic calculations of second-phase particle dissolution and analysis of grain boundary migration activation energy, a triggering criterion for abnormal grain growth was proposed: the volume fraction of pinning particles decreases below the critical value. This mechanistic explanation provides a theoretical basis for avoiding mixed grain defects in the heat treatment procedures of 45 steel after repeated heating or repair welding.

Although the review paper Tempering Transformation of Bainite Microstructures written by Liu Zongchang and Ji Yunping [5] does not specifically focus on 45 steel, its systematic discussion on the rearrangement of dislocation substructures and the habit planes of carbide precipitation in bainitic ferrite during tempering lays an important theoretical foundation for understanding the temper softening behavior in the core regions of large cross-sections of 45 steel, where partial bainite microstructures often form due to insufficient cooling rates.

1.5. Temper Softening Law and Hardness Prediction

This section discusses the overall variation trend of tempering hardness of 45 steel with different process parameters. In their research on the tempering behavior of acicular ferrite steel, Kang Junyan et al. [6] characterized the microstructural evolution that the lath matrix undergoes prominent recovery and sharp reduction in dislocation density at temperatures above 500 °C. This mechanism can also account for the general law of hardness reduction of 45 steel within this temperature range. Taking carbide-free bainitic steel as the research material, Cheng Yefeng et al. [7] established a hardness prediction model that couples tempering temperature and holding time into a unified tempering parameter. By introducing correction terms of material constants, such modeling strategy can offer semi-quantitative calculation references for the hardness prediction of 45 steel under tempering processes.

1.6. Explorations on Innovative Processes

In recent years, a number of exploratory studies with promising engineering application potential have emerged concerning the improvement and innovation of heat treatment processes for 45 steel. Targeting the spacer ring of armored vehicles as a specific component, Yan Xiaohong et al. [8] investigated the applicability of intercritical quenching. The results reveal that reducing the quenching heating temperature from the conventional temperature above 830 °C to approximately

780 °C enables the formation of a multiphase microstructure consisting of fine martensite and a small amount of acicular ferrite. Without obvious degradation in strength and hardness, this process effectively enhances the strength-toughness balance of the material, while lowering the tendency of quenching cracking and dimensional distortion. Such a process route possesses certain application value for small-sized 45 steel workpieces with complex geometries.

In terms of optimizing quenching cooling modes, researchers have proposed a time-controlled water bath quenching method [9]. Experimental data demonstrate that the cooling rate of water bath quenching at 820 °C is slower than that of full water quenching, leaving a small fraction of proeutectoid ferrite in the microstructure. After tempering at 450 °C, the strength and hardness are slightly inferior to those of fully water-quenched specimens, whereas toughness is remarkably improved. Evaluated from the perspective of comprehensive strength and toughness, the combined process of time-controlled water bath quenching at 820 °C followed by tempering at 450 °C achieves the optimal performance. This indicates that moderately sacrificing hardness to improve toughness can bring positive gains in overall service performance.

Furthermore, high-pressure heat treatment has attracted attention as a special processing route. To address the insufficient hardening depth and inferior mechanical strength of 45 steel after conventional atmospheric quenching and tempering, relevant research carried out quenching and tempering treatments under high-pressure environments [10]. Under a pressure of 3 GPa, the specimens were austenitized at 900 °C for 15 min, quenched, and then tempered at 550 °C for 60 min. A uniform and dense tempered sorbite microstructure with finely dispersed carbide particles was obtained. The hardness reached 36.3 HRC, and the compressive yield strength was 971 MPa, which were approximately 12% and 18% higher than those of specimens treated with the identical heat treatment schedule under atmospheric pressure, respectively. This study provides a novel technical approach for manufacturing structural components with high specific strength, yet the industrial practicability and economic efficiency of high-pressure equipment remain to be further evaluated.

2. Conclusions

Systematic review of the aforementioned literature reveals several common characteristics of current research in this field:

(1) Sufficient understanding has been achieved regarding process sensitivity. The influence trends and approximate magnitude of tempering temperature, holding duration and cooling mode on material hardness, strength and toughness have been cross-verified by numerous studies. The criteria for selecting process windows have become well-established, guaranteeing high reliability in engineering applications.

(2) A general consensus has been reached on the interpretation of

micro-mechanisms. Observations from various research groups show favorable self-consistency and repeatability with respect to lath martensite decomposition, the precipitation sequence of carbides (metastable ε-carbides transform into stable θ-cementite, followed by Cr-containing $M_{23}C_6$-type carbides), and the interfacial drag effect of chromium atoms.

(3) Short-term tempering dominates the experimental cycles. Most holding durations adopted in existing literature range from tens of minutes to more than ten hours, consistent with the standard cycle of quenching and tempering treatment in industrial manufacturing. Nevertheless, data on microstructural evolution over thousands of hours or even longer time scales remain scarce for components serving under prolonged high-temperature environments. Sufficient experimental support is lacking for evaluating microstructure stability under long-term service conditions.

(4) Research on the universality of composition fluctuations is relatively inadequate. Minor fluctuations in the contents of silicon, manganese and other elements are inevitable during mass industrial production. Existing tempering kinetic models lack systematic experimental verification and theoretical modification to accommodate such compositional deviations.

3. Conclusions and Prospects

This paper reviews the research progress regarding high-temperature tempering of 45 steel. The review reveals that existing studies on 45 steel mainly concentrate on general process defect control, fatigue damage regulation, high-temperature plasticity evaluation and innovative process development.

Future research in this field can focus on the following directions:

First, develop accelerated testing methods for evaluating long-term service performance to address the deficiency of long time-scale data in current research.

Second, establish predictive models for process parameters that incorporate the tolerance range of compositional fluctuations, so as to expand the application scope of research outcomes.

Third, advance the in-depth integration of multi-scale characterization and computational numerical simulation to realize correlated performance prediction covering scales from atomic level to full component level.

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