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Research Progress on Fatigue Damage Behavior and Performance Improvement of High Strength Steel Materials at High Temperature

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Abstract

The fatigue failure of high-strength steel in high temperature environment is a bottleneck problem restricting the reliability of key equipment such as nuclear power and aero-engine. In this paper, the microscopic mechanism of high temperature fatigue damage, life prediction models and performance improvement strategies are reviewed, with emphasis on cyclic softening/hardening behavior, martensite slab coarsening and crack initiation mechanisms. The applicability of macroscopic phenomenological model, crystal plasticity model and defect fracture mechanics model is compared and analyzed. The ways of performance optimization are discussed from three aspects: alloy design, surface strengthening and heat treatment technology, which provide theoretical reference for anti-fatigue design of high strength steel.

Keywords

High Strength Steel; High Temperature Fatigue; Micromechanism; Life Prediction; Performance Optimization.

1. Introduction

With the development of modern industry towards high temperature, high pressure and high parameters, high-strength steel is a key structural material for high-end equipment manufacturing, and its reliability under extreme conditions directly affects the safety and life of equipment. However, high temperature will weaken the mechanical properties of materials, accelerate fatigue damage and cause component fracture, resulting in major economic losses and potential safety hazards [1]. Therefore, it has become an urgent demand in the field of materials to study the evolution of fatigue damage of high-strength steel at high temperature, establish a life prediction model, and improve its fatigue performance through composition optimization and surface strengthening. The particularity of high-strength steel fatigue at high temperature lies in the strong coupling effect of multiple factors such as "environmental erosion-time accumulation-microscopic instability". Different from the single mechanical load dominant mode of fatigue at room temperature, at high temperature, the oxide scale peels off to form surface defects, and together with cyclic thermal stress, it accelerates the crack initiation; The creep-fatigue interaction caused by thermo-mechanical coupling effect leads to the accumulation of inelastic strain, which induces "cyclic softening"; More importantly, increased atomic diffusion promotes martensitic lath coarsening, carbide aggregation, and dislocation annihilation, resulting in a decrease in strength and accelerated crack growth [2]. In addition, life prediction needs to couple oxidation kinetics, creep equations and microscopic evolution models, and the technical complexity is significantly improved [3]. Existing studies mostly focus on a single mechanism, lacking the systematic correlation of "damage feature-performance improvement". This paper systematically reviews the micro-mechanism of high temperature fatigue damage, life

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prediction models and performance improvement strategies, in order to provide theoretical support for the fatigue design of high strength steels.

2. Fatigue Damage Behavior and Micromechanism of High Strength Steel at High Temperature

2.1 Macro-mechanical Response Behavior and Microstructure Evolution

Metallic materials usually exhibit cyclic softening or hardening behavior at high temperatures, depending on the strain amplitude: at low strain amplitude (< 0.25%), dislocation recombination and dynamic recovery dominate cyclic softening; At high strain amplitude (≥ 0.35%), dislocation entanglement initiates cyclic hardening. The high temperature environment further enhances the softening effect by accelerating the diffusion process. Under the interaction of creep and fatigue, the extension of retention time aggravates creep damage, creep damage is the main damage under low frequency loading, and fatigue damage is the main damage under high frequency loading, but it is indirectly affected by heat accumulation [2]. During cyclic loading at high temperature, the coarsening of martensite lath is the key factor leading to cyclic softening. The crystal plasticity model reveals the nonlinear growth law of slab width with the number of cycles: it increases rapidly at the initial stage, then slows down and tends to be stable [2]. This coarsening stems from a recovery process driven by dislocation recombination and interfacial energy reduction, which is more pronounced at high temperature and high strain amplitude $\Delta\varepsilon = 1.0\%$, and ultimately leads to a reduction in material strength. As the carrier of plastic deformation, the movable dislocation density decreases rapidly at the initial stage of the cycle, while the dislocation dipole density increases. After the two tend to stabilize, the overall dislocation recombination leads to accelerated softening [3].

The evolution of carbide during tempering has a decisive significance for the strength-toughness matching. Rapid induction tempering (heating rate 50-100 °C/s) can significantly refine the carbide size (about 40nm vs 90nm) and increase the spheroidization rate (84.4% vs 64.3%) compared with ordinary tempering $5°C/s$, which can be explained by the Ostwald maturation mechanism: rapid heating inhibits the long-range diffusion of carbon atoms, makes carbides disperse in the lath, and avoids grain boundary chain segregation [4]. Nanoscale MC-type carbides (2 ~ 5nm) precipitated by microalloying elements such as V and Nb hinder dislocation slip through dislocation pinning effect, inhibit the reduction of dislocation density during high temperature recovery, compensate for high temperature softening effect, and realize strength Synergistic improvement of plasticity [4].

Grain boundary and ferrite are weak links in microstructure. As a soft phase, ferrite has poor ability to coordinate with martensite matrix, and stress concentration is easy to occur at the interface to become the source of cracks; Carbide segregation at grain boundaries (M2C type) further aggravates the weakening effect [2]. Crystal plasticity simulation shows that fatigue damage localizes at grain boundaries and the intersection region of three crystals, and the orientation difference is conducive to dislocation plugging, resulting in boundary weakening and intergranular crack initiation.

Therefore, composition design and process optimization should focus on inhibiting ferrite formation and grain boundary embrittlement.

2.2 Fatigue Crack Initiation and Propagation

Carburizing treatment endows high-strength steel with an ideal performance combination of "high surface hardness and high core toughness", and there is a transition from "surface crack initiation" to "internal crack initiation" at the crack initiation location. Shot peening is the key means to regulate this transition [5]. The high surface hardness and residual compressive stress together inhibit the initiation of micro-cracks after carburization, and the excellent toughness of the core bears plastic deformation, so the cracks preferentially originate from surface defects without shot peening. Moderate shot peening can repair the original surface defects, introduce deep residual compressive stress layer, improve the surface anti-crack initiation ability, and force the crack initiation position to transfer to the interior; However, too high shot peening strength will lead to surface mechanical damage, which will reduce the fatigue life [6, 7].

The type and distribution of fatigue crack initiation sources determine the fatigue life of materials. Engineering failure cases show that the weld area is a typical source of initiation due to geometric discontinuity, welding residual stress, porosity, inclusion and other machining defects [8]. From the perspective of material structure, carbide, as a hard second phase, is easy to cause stress concentration due to incongruence with the deformation of the matrix, and becomes the core source of internal germination. The experimental observation confirmed that the fatigue cracks originated from the accumulation of carbides in the interior, and were accompanied by the fine grain region around [5]. Crack initiation is the initial link of "localized plastic damage from accumulation to instability". The location and timing of its occurrence directly determine the total life length, and the initiation life occupies a dominant position in the total fatigue life [2, 3] (Figure 1).

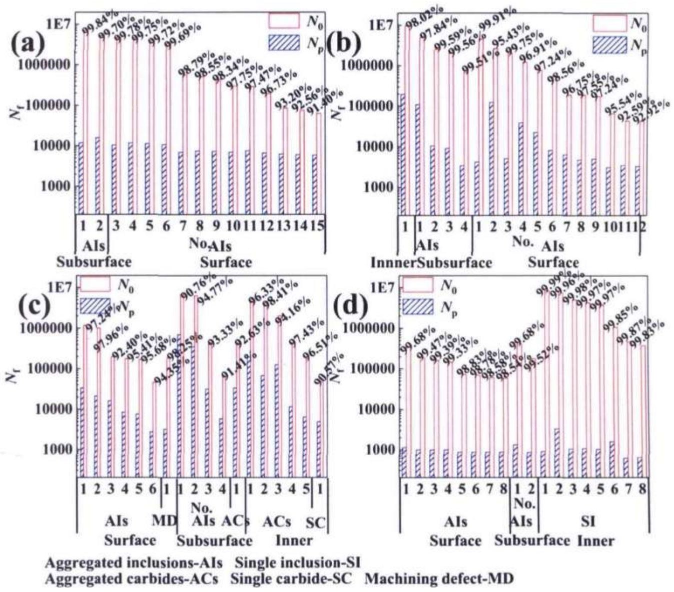

Figure 1. Distribution of crack initiation and propagation life under different working conditions [3]

3. Life Prediction Methods and Theoretical Models

3.1 Macro Phenomenological Model and Micro Physical Model

S-N curve is a classical tool to describe the relationship between stress amplitude and fatigue life, which is suitable for high cycle fatigue prediction. At high temperature, the yield strength and creep resistance of the material decrease, and the S-N curve shifts to the lower right. The results show that the fatigue ultimate strength of G13Cr4Mo4Ni4V steel decreases by 21-30% at 315 °C, which is the result of the combined effect of high temperature softening and oxidation accelerated crack growth [3]. The S-N curve method often introduces temperature correction factors to fit high temperature data, but does not consider microscopic mechanism changes, and the prediction accuracy is limited [9]. The crystal plasticity model can effectively describe the dislocation slip/climb and martensitic lath coarsening behavior by coupling the thermally activated constitutive equation, and explain the dislocation recombination and lath widening caused by high temperature dynamic recovery (the lath width increases from 236.67 nm to 249.05 nm after quenching at 1100 °C) [2]. The comparative analysis of fatigue indicator factors (FIPs) shows that the prediction accuracy of accumulated energy dissipation (W) is better than that of accumulated plastic slip (P) at high temperature and high strain amplitude, because W takes into account the thermo-mechanical coupling effect (the relative error of W at 315 °C is only 10%, while P is 15%), especially suitable for the working conditions where the interaction between oxidation and creep is significant [2]. Based on the crack growth zone model, direct calculation of the stress intensity factor using the defect projected area a can avoid the limitation of traditional crack length measurement, and successfully predict crack initiation in the carbide accumulation zone (a ≥ 400 μm2) [9].

3.2 Fracture Mechanics Model based on Defect

The stress intensity factor K is used to quantify the stress concentration at the defects (inclusions and aggregated carbides) in the fracture mechanics model based on defects, which is used as the critical criterion for fatigue crack initiation and propagation. At high temperature, the softening and oxidation of the material aggravate the stress concentration at the defect and reduce the K threshold, but the optimized shot peening can introduce residual compressive stress near the defect and effectively suppress the crack initiation [3, 5]. The size and distribution of defects are the most direct controlling factors of K, and aggregated carbides are more likely to lead to high K than single inclusions. Increasing temperature reduces the crack growth threshold ΔK from 4.50 MPa · m at room temperature to 4.20 MPa · m at 315 °C [5]. The fatigue properties can be improved effectively by optimizing the uniformity of structure, controlling the shot peening strength (optimal 0.2 mmA), designing the compressive stress gradient of the infiltration layer and superalloying.

3.3 Evaluation of the Applicability of Various Models

Multi-scale model coupling (correlation between microscopic mechanism and macroscopic damage) is the key to improving high temperature fatigue performance [2], and the development and verification of life prediction models in complex service environments is an important development direction.

As shown in the following table, this table compares the applicability characteristics of the four types of life prediction models from four aspects: applicable fatigue stages, load types, advantages and disadvantages:

Table 1. Comparison of Applicability of Various Life Prediction Models

Model Type	Applicable Fatigue Stage	Applicable Load Type	Advantages	Disadvantages
Macro-phenomenological Model (S-N Curve)	Full life (high cycle)	High-cycle fatigue	Simple, easy to use, based on experimental data	Ignores microscopic mechanisms; low accuracy at high temperatures
Macro-phenomenological Model (Manson-Coffin)	Initiation stage (low cycle)	Low-cycle fatigue	Describes plastic damage; applicable at high temperatures	Does not consider crack propagation or creep interaction
Microscopic Model (Crystal Plasticity + FIPs)	Initiation stage	Low-cycle/high-cycle	Clear physical mechanisms; high prediction accuracy	Complex, many parameters; high computational cost
Fracture Mechanics Model (Kdefect)	Propagation stage	High stress amplitude	Quantifies defect effects; applicable to defective materials	Dependent on defect size; not applicable to initiation

Overall, the macro model focuses on engineering practicality (full life of S-N curve, Manson-Coffin low cycle initiation), the micro model emphasizes physical mechanism and accuracy, and the fracture mechanics model focuses on defect expansion, which needs to be selected according to specific scenarios.

4. Strategies to Improve High Temperature Fatigue Performance

4.1 Alloy Design and Microstructure Optimization

Microalloying is an effective way to improve high temperature strength and toughness.

When V/Nb steel is tempered, the precipitated nano-scale VC and NbC hinder dislocation slip through dislocation pinning effect, inhibit the reduction of dislocation density during high temperature recovery, hinder grain boundary migration to delay recrystallization, and compensate for high temperature softening effect [4]. The aging strength (yield strength 1947 MPa, tensile strength 2197 MPa) of 18Ni martensitic steel is greatly improved compared with the solid solution state, and the elongation maintains 8.2%. While "strengthening", the nano-scale B2 phase "compensates for high temperature softening" by inhibiting excessive recovery/recrystallization "(Figure 2) [4]. The mechanical response of 18Ni martensitic steel in the figure further supports this mechanism: the strength of the aged sample (yield strength 1947 MPa, tensile strength 2197 MPa) is greatly improved compared with the solid solution state, and the elongation maintains 8.2%, indicating that the nano-scale B2 phase (analogous to VC, NbC strengthened phase) "compensates for high temperature softening" by suppressing excessive recovery/recrystallization while "strengthening"; The strength peak value of the experimental steel is more significant after tempering due to more sufficient VC precipitation, and the microalloying strengthening path of "V/Nb → VC/NbC precipitation → pinning dislocation + compensating softening → improving strength and toughness" is also verified from the side.

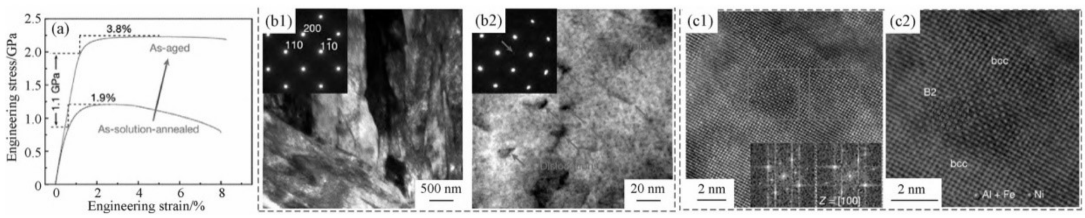

Figure 2. Comparison of mechanical responses of 18Ni martensitic steel in solid solution state and aging state [4]

Heavy warm rolling (HWR) achieves austenite ultra-refinement through "multi-stage deformation-relaxation-temperature matching", breaking through the bottleneck of grain refinement [1]. Taking 0.31 C-0. 70Si-0. 71Mn-3. 31Cr-0. 52Mo-0. 29V steel as an example, after multi-stage deformation (total strain 78.9%) and intermediate relaxation treatment, ultra-fine austenite with equivalent particle size of 0.57 μm was obtained. After quenching, it was transformed into fine martensitic lath, which was strengthened by Hall-Petch relationship [1]. The synergistic effect of carbide dispersion precipitation and fine grain strengthening makes the material achieve ultra-high strength (tensile strength 2411 MPa) and good plasticity (elongation 11.7%) [1].

4.2 Surface Strengthening Technology

Shot peening improves the fatigue performance by introducing residual compressive stress, but there is a "strengthening-overloading" characteristic. The test results show that the S-N curves of AISI4030 steel with different strength levels shift to the right and the fatigue life is prolonged after shot peening; The fatigue life of shot peened samples of SAE9245 martensitic steel is better than that of unshot peened samples in the whole life cycle [1]. The fatigue limit of martensitic steel shows a non-monotonic change of "rising first and then falling" with the increase of shot peening strength. Moderate shot peening optimizes the residual stress field and suppresses the initiation of defects. Excessive shot peening causes surface damage and residual stress relaxation, resulting in performance deterioration [1] (Figure 3). Therefore, it is necessary to strictly control the process window.

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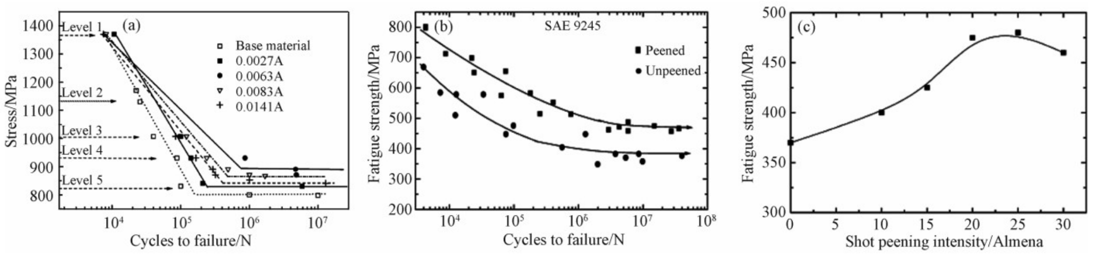

Figure 3. Non-monotonic relationship between shot peening strength and fatigue limit [1]

For welded joints, ultrasonic impact treatment has the best effect, and its characteristic fatigue strength and fatigue limit are increased by 65% and 102% respectively, which is far better than sanding and TIG dressing [8]. The physical mechanism is that ultrasonic impact introduces compressive residual stress in the surface layer to offset the external tension stress, and at the same time optimizes the geometry of the joint to a smooth transition arc surface, which cooperatively reduces the stress concentration factor and effectively suppresses crack initiation and propagation [8].

4.3 Innovation of Heat Treatment Process

Electromagnetic induction tempering (EMI) exhibits significant advantages in heat treatment of 1000MPa grade low carbon ultra high strength steel. Compared with ordinary tempering (5 °C/s), induced tempering (50-100 °C/s) regulates the carbide behavior in three aspects: inhibiting the long-range diffusion of carbon atoms, refining the carbide size to 40nm; Promote spheroidization, the spheroidization rate reaches 84.4%; Carbides are dispersed and distributed in the lath to avoid chain segregation at grain boundaries [4]. These characteristics are translated into excellent mechanical properties: the yield strength is above 1050MPa, the impact energy is 139J (0 °C), and the strength-toughness ratio is significantly better than that of ordinary tempering (the yield strength is about 975MPa, the impact energy is 60-75J) [4]. The high supersaturation caused by rapid heating is conducive to the precipitation of fine spherical carbides and strengthens the Orowan bypass mechanism. At the same time, the uniformly distributed carbides delay crack growth and break through the strength-toughness inversion relationship [4]. There is a non-monotonic relationship between hardness and wear resistance. The hardness of quenched martensite is the highest but the wear resistance is poor (wear rate 8.06). After induction tempering at 500 °C, the hardness decreases to 396.3 HV, and the wear rate decreases to 4.65 [4]. This is due to the transformation of wear mechanism caused by the evolution of microstructure: quenched martensite is brittle, the main wear mechanism is micro-cutting, and brittle spalling is easy to occur; After tempering, the carbides are spheroidized, refined and dispersed, the toughness of the matrix is improved, the wear mechanism changes to micro-ploughing and fatigue, the wear scars are shallow and multi-directional, and the anti-fatigue spalling ability is enhanced [4]. Therefore, optimizing carbide morphology (spheroidization) and distribution (dispersion) to improve toughness and control wear mechanism is the correct way to achieve high wear resistance.

5. Research Limitations and Future Prospects

At present, high-temperature fatigue research is facing multiple bottlenecks: there are significant differences between a single high-temperature environment in the laboratory and the actual "thermal-mechanical-environmental" multi-field coupling conditions, which limit the engineering applicability of theoretical models; There is no effective correlation between the microscopic mechanism and the macroscopic life prediction model, and it is difficult to achieve cross-scale prediction from the atomic scale to the element scale; There is a serious lack of research on high temperature and ultra-high cycle fatigue behavior, and the existing data are concentrated in the range of medium and low cycles, which cannot support the design of long-life components; The "double-edged sword effect" of surface strengthening technology makes the parameter control face challenges. Future research should focus on: developing nonlinear damage accumulation models based on dislocation entanglement and carbide interface debonding; Combining machine learning and crystal plasticity simulation, mining the "structure-property" correlation to accelerate the design of new materials; Develop high-temperature in-situ characterization technology to capture microscopic dynamic processes in real time; Build an atom-mesoscopic-macro full-chain multi-scale model and a digital twin system to realize real-time mapping between models and real components. Through the closed loop of "mechanism-model-experiment-digital", it breaks through the bottleneck of high-temperature fatigue research and provides support for the precise design, operation and maintenance of long-life parts.

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