Study on High-Cycle Fatigue Performance of FV520B Steel Based on Intrinsic Dissipation (Postprint)

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Abstract

Based on intrinsic dissipation theory and computational models, a relatively systematic experimental investigation was conducted on the high-cycle fatigue performance of FV520B steel. The results indicate that as the applied alternating stress amplitude increases, the intrinsic dissipation of FV520B steel also increases continuously. The inflection point in its variation pattern corresponds to a transition in the intrinsic dissipation generation mechanism: from being caused solely by reversible motion of material microstructures (oscillation of dislocation lines between strong pinning points) to being caused jointly by both reversible and irreversible motions of material microstructures (generation of permanent slip, depinning of strong pinning points, and dislocation multiplication). Moreover, the stress amplitude at the intrinsic dissipation inflection point is precisely the critical stress amplitude that leads to fatigue damage accumulation in the material, i.e., the fatigue limit. Additionally, experiments also demonstrate that FV520B steel exhibits a relatively stable damage evolution rate under constant-amplitude alternating stress, and this damage evolution rate is determined by the stress amplitude and independent of the loading sequence; the fatigue damage caused per loading cycle is also unaffected by the loading frequency. When the accumulated portion of intrinsic dissipation associated with irreversible evolution of microstructures in FV520B steel during the fatigue process reaches a critical value, the material undergoes fatigue fracture, and this critical value is a material constant independent of loading history.

Full Text

Research on High-Cycle Fatigue Behavior of FV520B Steel Based on Intrinsic Dissipation

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Abstract

Systematic experimental research was carried out on the high-cycle fatigue behavior of FV520B steel based on the theory and calculation model of intrinsic dissipation. The results show that the intrinsic dissipation of FV520B steel increases with increasing applied stress amplitude. Generally, the inflection point of intrinsic dissipation corresponds to the transition of its generation mechanism: from the reversible motion of microstructure (the swing of dislocation lines between strong pinning points) to the combined effects of reversible and irreversible microstructure motion (the generation of permanent slip, unpinning from strong points, and dislocation multiplication). Moreover, the stress amplitude corresponding to this inflection point represents the critical stress value that induces fatigue damage accumulation—the fatigue limit. Additionally, FV520B steel subjected to constant stress amplitude maintains a relatively steady damage evolution rate that depends only on the stress amplitude and is independent of loading sequence. The fatigue damage per loading cycle is also unaffected by loading frequency. Fatigue failure occurs once the accumulated intrinsic dissipation related to irreversible microstructure evolution reaches a threshold value, which is found to be a material constant independent of loading history.

Keywords: FV520B steel, intrinsic dissipation, high-cycle fatigue, microstructure motion

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Introduction

FV520B steel is a novel low-carbon martensitic precipitation-hardening stainless steel developed by the UK Firth-Vickers Materials Research Laboratory based on the original FV520 steel. It exhibits high strength, toughness, and excellent corrosion resistance and weldability, making it widely used in industrial equipment manufacturing for aerospace, petrochemical, and other fields. While substantial research has been conducted on the mechanical properties of FV520B steel, most studies have focused on strength, plasticity, and toughness, with relatively few investigations addressing its high-cycle fatigue performance. However, with rapid industrial development, fatigue design has become a critical aspect of product development, making research on the high-cycle fatigue behavior of FV520B steel scientifically valuable and practically significant.

As an irreversible thermodynamic process, high-cycle fatigue of FV520B steel inevitably leads to energy dissipation. Energy methods based on intrinsic dissipation represent an important approach for studying material high-cycle fatigue performance. By monitoring the surface temperature of loaded specimens using high-precision infrared thermography and processing the data to obtain energy information related to fatigue damage, researchers can effectively investigate high-cycle fatigue problems. Previous studies have employed various techniques: references [9–11] performed local fitting of temperature signals in both temporal and spatial domains, combined with established local heat conduction equations for thin plate specimens, to achieve separation of different heat sources. Connesson et al. [12,13] imported synchronous load signals to eliminate thermoelastic effects from temperature signals and used reference specimens to offset environmental fluctuations, enabling accurate measurement of dissipation energy during initial loading cycles. References [14–17] calculated energy dissipation under corresponding loads using temperature changes during loading interruption and evaluated fatigue life based on this indicator. Meanwhile, numerous domestic scholars have conducted extensive related research. Tong et al. [18,19] and Yao et al. [20] analyzed the correlation between energy dissipation and surface microstructure evolution during fatigue and established damage models based on energy dissipation. Zeng et al. [21] and Li et al. [22] calculated the dissipation energy per cycle related to high-cycle fatigue damage under different stress amplitudes and fitted dissipation energy-fatigue life curves. Zhang et al. [23] and Liu et al. [24] elaborated on the temperature evolution mechanism during high-cycle fatigue. References [25–27] constructed an intrinsic dissipation calculation model based on one-dimensional double exponential regression of surface temperature rise in loaded specimens and proposed an energy method for rapid assessment of material fatigue performance.

This work presents a systematic experimental study on the high-cycle fatigue performance of FV520B steel based on intrinsic dissipation theory and calculation models. The results are analyzed and discussed in combination with the Granato-Lücke dislocation pinning model and Frank-Read dislocation multiplication theory to further refine relevant theories and methods and provide high-cycle fatigue data support for the engineering application of FV520B steel.

1.1 Intrinsic Dissipation Theory

From the perspective of continuum thermodynamics, high-cycle fatigue of materials can be studied as a quasi-static irreversible thermodynamic process. To accurately describe this process, the selected state variables include not only thermodynamic temperature T and strain tensor ε but also a set of additional state variables α_n $(n = 1, 2, \dots, N)$ that characterize non-equilibrium dissipation processes within the material. Combining the first and second laws of thermodynamics and introducing the Helmholtz free energy per unit mass ψ, the local state equation for materials during high-cycle fatigue can be expressed as [9-11]:

$$\rho C\dot{T} - \mathrm{div}(k\nabla T) = \sum_{n=1}^{N} \rho \frac{\partial \psi}{\partial \alpha_n}\dot{\alpha}_n + \sigma : \dot{\varepsilon} - \rho \frac{\partial \psi}{\partial \varepsilon} : \dot{\varepsilon} + \rho \frac{\partial \psi}{\partial T}\dot{T}$$

where r is the external volumetric heat source, σ is the Cauchy stress tensor, and ρ, C, and k are the material density, specific heat capacity, and thermal conductivity, respectively. The superscript dot denotes the material time derivative of the corresponding variable. The first term on the left side, $\rho C\dot{T}$, represents the rate of heat storage (or release) characterized by temperature change, while the second term, $-\mathrm{div}(k\nabla T)$, represents heat loss due to thermal conduction. The first three terms on the right side collectively represent the heat source caused by intrinsic dissipation (abbreviated as intrinsic dissipation), the fourth term is the thermoelastic source, and the fifth term arises from the coupling between internal variables and temperature.

Intrinsic dissipation d_1 is essentially the energy manifestation of the entropy production component not caused by heat conduction per unit time during high-cycle fatigue [9-11,28,29]:

$$d_1 = T\dot{s}_i = T(\dot{s} - \dot{s}_e)$$

where $\dot{s}$ is the entropy increase rate and $\dot{s}_e$ represents the portion of entropy production rate caused by heat conduction, whose energy manifestation is called thermal dissipation. According to the Clausius-Duhem inequality, the entropy production rate, as a quantitative objective characterization of the irreversible process, is always greater than zero, and thus the intrinsic dissipation d_1 is also always greater than zero. Due to inevitable defects within the material (such as vacancies, dislocations, grain boundaries, etc.), irreversible evolution of microstructure still occurs even under relatively low alternating stresses (dislocation intersection, multiplication, pile-up, etc.), leading to entropy production and manifesting as intrinsic dissipation. This makes intrinsic dissipation highly sensitive to microstructural changes. These continuous irreversible microstructural changes cause fatigue damage and ultimately lead to fatigue fracture. Therefore, using intrinsic dissipation to characterize the fatigue damage process has clear physical significance. However, it should be noted that intrinsic dissipation is not solely caused by irreversible changes in material microstructure. In fact, stress-induced ordering of solute atoms, viscous friction at grain boundaries, and small oscillations of dislocation lines under alternating stresses also contribute to intrinsic dissipation, although these effects do not cause irreversible microstructural changes and thus do not substantially contribute to fatigue damage.

1.2 Intrinsic Dissipation Calculation Model

As an irreversible energy dissipation process, high-cycle fatigue inevitably causes temperature changes in the material. Extensive fatigue experiments have shown that when the applied alternating stress is below the yield limit, the temperature evolution exhibits three stages: initial temperature rise, temperature stabilization, and rapid temperature increase before fracture. The temperature stabilization stage occupies approximately 90% of the entire fatigue life. During this stage, the heat generated by the material remains in dynamic balance with heat loss due to thermal conduction, convection, and radiation, with temperature exhibiting only periodic fluctuations synchronized with the loading frequency under thermoelastic effects. Through equation (1) and some reasonable assumptions, a one-dimensional heat conduction equation for slender thin-plate specimens within the gauge length can be obtained:

$$\rho C\frac{\partial\theta}{\partial t}+\frac{1}{\tau}\theta=k\frac{\partial^2\theta}{\partial x^2}+\dot{s}_{the}+\dot{s}_{1D}$$

where t is time, x is the coordinate, $\theta=T-T_0$ is the temperature rise during high-cycle fatigue, and τ is a time constant characterizing the specimen' s ability to exchange heat with the external environment (through convection and radiation). By averaging equation (3) over a certain number of cycles in the time domain, we obtain:

$$\rho C\frac{\partial\hat{\theta}}{\partial t}+\frac{1}{\tau}\hat{\theta}=k\frac{\partial^2\hat{\theta}}{\partial x^2}+\hat{\dot{s}}_{the}+\hat{\dot{s}}_{1D}$$

where the superscript hat denotes the average of the corresponding variable over the time domain. When the specimen is in the temperature stabilization stage, the temperature change rate $\dot{\hat{\theta}}$ and the thermoelastic source $\hat{s}_{the}$ both vanish over integer loading cycles, i.e., $\dot{\hat{\theta}}=0$ and $\hat{s}_{the}=0$. Therefore, equation (4) simplifies to a second-order linear ordinary differential equation with constant coefficients:

$$k\frac{d^2\hat{\theta}}{dx^2}-\frac{1}{\tau}\hat{\theta}+\hat{s}_{1D}=0$$

Its general solution can be expressed as:

$$\hat{\theta}(x) = C_1 \exp\left(\sqrt{\frac{1}{k\tau\rho C}}x\right) + C_2 \exp\left(-\sqrt{\frac{1}{k\tau\rho C}}x\right) + P(x)$$

where C_1 and C_2 are arbitrary constants. Equation (6) indicates that the average temperature rise $\hat{\theta}(x)$ over several consecutive whole cycles during high-cycle fatigue follows a double exponential function distribution within the specimen gauge length:

$$\hat{\theta}(x) = C_1 e^{-r_1 x} + C_2 e^{-r_2 x} + C_3$$

where C_1 and C_2 are coefficients determined by temperature boundary conditions, r is a parameter determined by the heat exchange performance between the specimen surface and the external environment, and C_3 is a coefficient jointly determined by this heat exchange performance and the material' s intrinsic dissipation. Based on this distribution form of the average temperature rise, the average intrinsic dissipation over the time domain is:

$$\hat{d}_1(x) = \frac{k}{\rho C}(r_1^2 C_1 e^{-r_1 x} + r_2^2 C_2 e^{-r_2 x})$$

It should be noted that in this experimental study, the 15-second interval before the end of each cyclic loading was used as the time domain for calculating the average intrinsic dissipation, which was then taken as the material' s intrinsic dissipation under that loading condition.

Experimental Material and Specimen

The experimental material was FV520B martensitic precipitation-hardening stainless steel plate, smelted in an alkaline electric furnace and then remelted by electroslag refining. Its main chemical composition (mass fraction, %) is: C 0.02-0.07, Si 0.15-0.70, Mn 0.3-1.0, Cr 13.0-14.5, Ni 5.0-6.0, Cu 1.3-1.8, Nb 0.25-0.45, S $\leq$ 0.025, P $\leq$ 0.03, Mo 1.3-1.8, Fe balance.

To improve the machinability of FV520B steel, the plates underwent heat treatment with the following process: (1) solution treatment at (1050$±10)$^{\circ}Cfor1hourfollowedbyaircooling;(2)intermediateadjustmenttreatmentat(850\pm10)^{\circ}Cfor2hoursf$ for 3 hours followed by air cooling. Tensile tests yielded the material' s ultimate strength $\sigma_b = 1343$ MPa and yield limit $\sigma_{0.2} = 1095$ MPa. Additionally, to accurately calculate the intrinsic dissipation during fatigue, the material' s thermal conductivity was experimentally determined as $k = 15\ \mathrm{W \cdot m^{-1} \cdot K^{-1}}$.

All specimens were cut from the same 5 mm thick steel plate, with their longitudinal direction aligned with the rolling direction. The specimen dimensions are shown in [Figure 1: see original paper]. Before testing, specimen surfaces were polished with fine sandpaper, particularly at edges and corners, to reduce stress concentration and minimize machining effects. Since an infrared thermal imager was used to record specimen surface temperature, a layer of black matte paint was sprayed on the surface to enhance thermal emissivity.

Experimental Setup and Loading Procedures

The experiments were conducted using an MTS810 hydraulic servo testing machine for uniaxial sinusoidal cyclic loading. Stress control mode was employed with a constant stress ratio $R = -1$. Temperature changes on the specimen surface during loading were monitored in real-time using a Cedip Jade III infrared thermal imager with a spectral response range of 3–5 m, thermal resolution of 0.005°C at 25°C, and noise equivalent temperature difference (NETD) of 0.02°C. To maintain relatively stable temperature boundary conditions during testing, circulating cooling water was continuously applied to the testing machine grips, and a small fan provided unidirectional airflow over the loaded specimen surface to maintain a stable convective environment.

All experiments employed stepwise loading, with 1×10^4 cycles at each load level, followed by unloading and cooling to room temperature before proceeding to the next level. The infrared thermal imager recorded the specimen surface temperature only during the 5 seconds before loading initiation (for initial temperature calculation) and the 15 seconds before loading termination (for average intrinsic dissipation calculation). During both intervals, the specimen reached thermal equilibrium with the environment, maintaining a relatively stable temperature.

The specific loading procedures were as follows:

1. **Stress amplitude effect study:** A new specimen was subjected to stepwise graded loading at 10 Hz. The first load level had a stress amplitude of $\sigma_a = 220$ MPa, the second $\sigma_a = 230$ MPa, and so on, increasing by 10 MPa per level until the final load level of $\sigma_a = 440$ MPa, as shown in [Figure 2a: see original paper].
2. **Loading sequence effect study:** A new specimen underwent seven sequences of graded loading at 10 Hz. Each sequence consisted of four load levels with stress amplitudes of 300, 320, 380, and 400 MPa, as shown in [Figure 2b: see original paper].
3. **Loading frequency effect study:** Graded loading experiments were conducted at frequencies of 5, 7.5, 10, 12.5, 15, 17.5, and 20 Hz. Each test consisted of five load levels with stress amplitudes of 300, 320, 340, 360, and 380 MPa.

Additionally, to investigate damage evolution throughout the entire fatigue life, intermittent constant-amplitude loading tests were performed on two new specimens at 10 Hz with stress amplitudes of 380 and 400 MPa. Loading was paused every 1×10^4 cycles, and after cooling to room temperature, loading resumed. This process repeated until specimen fracture. The infrared thermal imager recorded surface temperature during the 5 seconds before resuming loading and the 15 seconds before each pause.

Experimental Results and Analysis

By processing the thermal image data acquired during experiments, the average temperature rise during the 15 seconds before each cyclic loading termination was obtained. Double exponential function regression analysis was then applied to determine the regression equation. Using parameters from the regression equation, the average intrinsic dissipation during the 15 seconds before loading termination was calculated via equation (8), representing the material's intrinsic dissipation under that loading condition.

[Figure 3: see original paper] shows the variation of intrinsic dissipation with stress amplitude for FV520B steel. The results demonstrate that intrinsic dissipation increases continuously with increasing stress amplitude. Moreover, a noticeable inflection occurs near $\sigma_a = 360$ MPa. The data pairs (σ_a, d_1) were divided into two regions and linearly fitted separately. The intersection of the two fitted lines determines the inflection point at a stress amplitude of 357.48 MPa, with slopes of 635.21 and 2436.59 for the lower and upper regions, respectively—nearly a fourfold difference. This phenomenon indicates a transition in the generation mechanism of intrinsic dissipation for high-cycle fatigue at the inflection point, corresponding to a change in microstructure motion mechanisms.

To analyze this behavior, we combine the Granato-Lücke dislocation pinning model and Frank-Read dislocation multiplication theory. Within the microstructure of FV520B steel, weak pinning points for dislocation lines exist, such as solute atoms and vacancies, while strong pinning points include second phases, dislocation tangles, and grain boundaries. For stress amplitudes below the inflection point, increasing stress amplitude causes dislocations to gradually unpin from weak pinning points and oscillate between strong pinning points. The area swept by dislocation line oscillation is proportional to intrinsic dissipation. Notably, this oscillation between strong pinning points is reversible and does not cause substantive changes in dislocation structure; dislocation lines return to their initial positions after stress unloading, resulting in no fatigue damage.

For stress amplitudes above the inflection point, dislocation lines deviate far from their equilibrium positions, causing permanent slip. As stress amplitude increases, strong pinning points begin to unpin and participate in slip, while some strongly pinned points that cannot unpin become dislocation sources, continuously generating new dislocations. The generation of permanent slip, unpinning of strong pinning points, and dislocation multiplication all constitute irreversible microstructural changes that cause entropy production and lead to a sharp increase in intrinsic dissipation. Such irreversible microstructural evolution is the fundamental cause of high-cycle fatigue damage. Therefore, the inflection point in intrinsic dissipation corresponds to a transition in its generation mechanism from purely reversible microstructure motion (dislocation oscillation between strong pinning points) to combined reversible and irreversible microstructure motion (permanent slip generation, strong pinning point unpinning, and dislocation multiplication). The stress amplitude at this inflection point represents the material' s fatigue limit.

Furthermore, [Figure 3: see original paper] reveals a good linear relationship between stress amplitude and intrinsic dissipation below the fatigue limit, where intrinsic dissipation should be entirely caused by reversible microstructure motion. Assuming this linear relationship remains valid above the fatigue limit (shown as the red dashed line in [Figure 3: see original paper]), the irreversible microstructure evolution component of intrinsic dissipation above the fatigue limit (360–440 MPa) can be calculated by subtracting the extrapolated values from the experimental data, as shown in [Figure 4: see original paper].

[Figure 5: see original paper] presents the evolution of intrinsic dissipation throughout the entire fatigue life at stress amplitudes of 380 and 400 MPa. The results show that intrinsic dissipation remains essentially stable overall, indicating that microstructure evolution proceeds at a relatively stable rate under constant stress amplitude. The damage evolution process during high-cycle fatigue can be quantitatively characterized by the accumulation of the intrinsic dissipation component related to irreversible microstructure changes. When this accumulated value reaches a critical threshold C, fatigue failure occurs, and this critical value is a material constant independent of loading history.

Based on the data at stress amplitudes of 380 and 400 MPa from [Figure 4: see original paper], the accumulated irreversible microstructure evolution component of intrinsic dissipation throughout the fatigue life—the critical value for fatigue failure—can be obtained. The critical values at these two stress amplitudes show little difference (1.3149×10^{10} and 1.2901×10^{10} J/m^3, respectively), partially validating the previous assumption regarding the reversible motion component above the fatigue limit. To reduce error, the average value of 1.3025×10^{10} J/m^3 was taken as the actual fatigue failure critical value C. Combining this with data from [Figure 4: see original paper], the fatigue life N_f at each stress amplitude was calculated. Using the least squares method, the stress-life data pairs (σ_a, N_f) were linearly fitted in double logarithmic coordinates to determine the S-N curve for FV520B steel at 50% survival probability, as shown in [Figure 6: see original paper].

[Figure 7: see original paper] shows the results of seven loading sequences on a single specimen. The results indicate no significant difference in intrinsic dissipation at the same stress amplitude across different sequences, demonstrating that high-cycle fatigue damage in FV520B steel is independent of loading sequence. In other words, the damage evolution rate depends only on stress amplitude and is unaffected by loading history. This also validates the feasibility of using a single specimen to determine intrinsic dissipation at different stress amplitudes. Additionally, according to the Granato-Lücke dislocation pinning model, intrinsic dissipation at 300 and 320 MPa should result from dislocation oscillation between strong pinning points. However, as fatigue damage evolves, this oscillation-induced intrinsic dissipation is not affected by strong pinning point unpinning or increased dislocation density.

[Figure 8: see original paper] presents the results of graded loading experiments at different frequencies. The results show that intrinsic dissipation increases proportionally with loading frequency at the same stress amplitude, indicating that fatigue damage per loading cycle is constant and independent of loading frequency. Therefore, it can be inferred that within the studied frequency range, the fatigue life of FV520B steel depends only on stress amplitude and is not influenced by loading frequency.

Conclusions

1. Intrinsic dissipation is essentially the energy manifestation of entropy production not caused by heat conduction per unit time. Using intrinsic dissipation as a fatigue damage indicator to quantitatively describe the evolution rate of material microstructure during high-cycle fatigue has clear physical significance.
2. FV520B steel maintains a relatively stable damage evolution rate under constant alternating stress amplitude, with the rate determined by stress amplitude and independent of loading sequence. The fatigue damage per loading cycle is also unaffected by loading frequency. When the accumulated irreversible microstructure evolution component of intrinsic dissipation reaches a critical threshold during fatigue, failure occurs, and this critical value is a material constant independent of loading history.

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Note: Figure translations are in progress. See original paper for figures.