# Postprint: Study on High-Cycle Fatigue Performance of FV520B Steel Based on Intrinsic Dissipation

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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 the intrinsic dissipation of FV520B steel continuously increases with increasing applied alternating stress amplitude. 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 jointly caused by both reversible and irreversible motions of material microstructures (generation of permanent slip, depinning of strong pinning points, and dislocation multiplication). Furthermore, the stress amplitude at the intrinsic dissipation inflection point represents the critical stress amplitude that leads to fatigue damage accumulation in the material, i.e., the fatigue limit. Additionally, experiments demonstrate that FV520B steel exhibits a relatively stable damage evolution rate under constant-amplitude alternating stress, with the damage evolution rate being 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 related to 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. The inflection point in this relationship corresponds to a transition in the generation mechanism of intrinsic dissipation: from being caused solely by reversible motion of material microstructure (swinging of dislocation lines between strong pinning points) to being caused by combined reversible and irreversible motion of microstructure (generation of permanent slip, unpinning from strong pinning points, and dislocation multiplication). Moreover, the stress amplitude corresponding to this inflection point represents the critical stress value that induces fatigue damage accumulation, i.e., the fatigue limit. The experiments also demonstrate that FV520B steel maintains a relatively stable damage evolution rate under constant stress amplitude, with the rate determined by stress amplitude and independent of loading sequence. Additionally, the fatigue damage per loading cycle is unaffected by loading frequency. Fatigue failure occurs when the accumulated intrinsic dissipation related to irreversible microstructural evolution reaches a critical value, which is found to be a material constant independent of loading history.

**KEY WORDS** FV520B steel, intrinsic dissipation, high-cycle fatigue, microstructure motion

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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 and toughness, along with good corrosion resistance and weldability, making it widely used in industrial equipment manufacturing for aerospace, petrochemical, and other fields. While extensive 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 performance of FV520B steel scientifically valuable and practically significant.

As an irreversible thermodynamic process, high-cycle fatigue of FV520B steel inevitably leads to energy dissipation, and energy methods based on intrinsic dissipation represent an important approach for studying material high-cycle fatigue performance. Monitoring and recording the surface temperature of loaded specimens using high-precision infrared thermography, then processing the data to obtain energy information related to fatigue damage, constitutes a key strategy for applying energy methods to fatigue problems. Previous work has employed spatiotemporal local fitting of temperature signals combined with established local heat conduction equations for thin-plate specimens to achieve separation of different heat sources. Other researchers have synchronized load signals to eliminate thermoelastic effects from temperature signals and used reference specimens to offset environmental fluctuations, enabling more accurate measurement of dissipated energy during initial loading cycles. Additional studies have calculated energy dissipation under corresponding loads using temperature changes during loading interruptions and used these values as indicators for fatigue life assessment. Domestic scholars have also conducted extensive related research, analyzing correlations between energy dissipation and surface microstructural evolution during fatigue and establishing damage models based on energy dissipation.

This work presents a systematic experimental study of 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 engineering applications of FV520B steel.

### 1.1 Intrinsic Dissipation Theory

According to fundamental principles 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 $\varepsilon$, but also a set of additional state variables, i.e., internal variables $\alpha_n$ $(n = 1, 2, \dots, n)$, that characterize non-equilibrium dissipation processes within the material. Combining the first and second laws of thermodynamics and introducing Helmholtz free energy per unit mass $\psi$, the local state equation for materials during high-cycle fatigue can be expressed as:

$$\rho C\dot{T} - \mathrm{div}(k \cdot \mathrm{grad}\ T) = \sigma : \dot{\varepsilon} - \rho \frac{\partial \psi}{\partial \alpha_n} \dot{\alpha}_n + \rho T \frac{\partial^2 \psi}{\partial T \partial \alpha_n} \dot{\alpha}_n + \rho T \frac{\partial^2 \psi}{\partial T \partial \varepsilon} : \dot{\varepsilon}$$

where $r$ is the external volumetric heat source; $\sigma$ is the Cauchy stress tensor; $\rho$, $C$, and $k$ are material density, specific heat capacity, and thermal conductivity, respectively; and the superscript dot denotes the material derivative of the corresponding variable. The first term on the left side, $\rho C\dot{T}$, represents the heat storage (or release) rate characterized by temperature change, while the second term $-\mathrm{div}(k \cdot \mathrm{grad}\ T)$ represents heat loss due to thermal conduction. The first three terms on the right side collectively represent the heat source caused by intrinsic dissipation (referred to as intrinsic dissipation $d_1$); the fourth term $\rho T \frac{\partial^2 \psi}{\partial T \partial \varepsilon} : \dot{\varepsilon}$ is the thermoelastic source $s_{te}$; and the fifth term $\rho T \frac{\partial^2 \psi}{\partial T \partial \alpha_n} \dot{\alpha}_n$ is the heat source $s_{tp}$ caused by coupling between internal variables and temperature.

Intrinsic dissipation $d_1$ is essentially the energy manifestation of the entropy production portion not caused by heat conduction during high-cycle fatigue:

$$d_1 = \rho T \dot{\eta}_i = \rho T (\dot{\eta} - \dot{\eta}_e) = \rho T (\dot{\eta} - \mathrm{div}(\mathbf{q}/T))$$

where $\dot{\eta}$ is the entropy increase rate and $\dot{\eta}_e = \mathrm{div}(\mathbf{q}/T)$ represents the portion of entropy production caused by heat conduction, whose energy manifestation is called thermal dissipation. According to the Clausius-Duhem inequality, entropy production rate, as a quantitative objective characterization of the irreversible process, is always greater than zero, and intrinsic dissipation $d_1$ is therefore also always greater than zero.

Since materials inevitably contain defects such as vacancies, dislocations, and grain boundaries, irreversible evolution of microstructure (dislocation intersection, multiplication, pile-up, etc.) occurs even under relatively low alternating stresses, causing 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 stress also contribute to intrinsic dissipation, though 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 materials. Numerous fatigue experiments have shown that when applied alternating stress is below the yield limit, material temperature evolution exhibits three stages: initial temperature rise, temperature stabilization, and rapid temperature rise before fracture. The temperature stabilization stage accounts for approximately 90% of the entire fatigue life. During this stage, heat generation and heat dissipation through thermal conduction, convection, and radiation remain in dynamic equilibrium, with temperature exhibiting periodic fluctuations synchronized with the loading frequency only 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:

$$\frac{\partial \theta}{\partial t} = \frac{k}{\rho C}\frac{\partial^2 \theta}{\partial x^2} - \frac{1}{\tau_{1D}}\theta + \frac{1}{\rho C}(d_1 + s_{te})$$

where $t$ is time; $x$ is the coordinate; $\theta = T - T_0$ (temperature rise) is the temperature increase during high-cycle fatigue; and $\tau_{1D}$ is a time constant characterizing the specimen' s surface heat exchange capability with the environment (through convection and radiation).

Averaging equation (3) over a certain number of cycles in the time domain yields:

$$\frac{\partial \bar{\theta}(x)}{\partial t} = \frac{k}{\rho C}\frac{\partial^2 \bar{\theta}(x)}{\partial x^2} - \frac{1}{\tau_{1D}}\bar{\theta}(x) + \frac{1}{\rho C}(\bar{d}_1 + \bar{s}_{te})$$

where the superscript bar denotes averaging over the time domain, and $\hat{\theta}$ represents the time derivative $\partial\theta/\partial t$ averaged over the time domain. When the specimen is in the temperature stabilization stage, the cumulative result of temperature change rate $\partial\theta/\partial t$ over integer loading cycles is zero, and the average thermoelastic source $\bar{s}_{te}$ is also zero, i.e., $\hat{\theta} = 0$ and $\bar{s}_{te} = 0$. Therefore, equation (4) simplifies to a second-order linear ordinary differential equation for $\bar{\theta}(x)$:

$$\frac{k}{\rho C}\frac{\partial^2 \bar{\theta}(x)}{\partial x^2} - \frac{1}{\tau_{1D}}\bar{\theta}(x) + \frac{1}{\rho C}\bar{d}_1 = 0$$

with the general solution:

$$\bar{\theta}(x) = P_1 \exp\left(\sqrt{\frac{\rho C}{k\tau_{1D}}}x\right) + P_2 \exp\left(-\sqrt{\frac{\rho C}{k\tau_{1D}}}x\right) + \tau_{1D}\frac{\bar{d}_1}{\rho C}$$

Equation (6) indicates that during high-cycle fatigue, the average temperature rise $\bar{\theta}(x)$ over several complete cycles exhibits a double exponential distribution within the specimen gauge length:

$$\bar{\theta}(x) = C_1 \exp(rx) + C_2 \exp(-rx) + C_3$$

where $C_1$ and $C_2$ are coefficients determined by temperature boundary conditions, $r$ is a parameter determined by the specimen surface heat exchange performance with the environment, and $C_3$ is a coefficient jointly determined by this heat exchange performance and material intrinsic dissipation. Based on this distribution form of $\bar{\theta}(x)$, the average intrinsic dissipation over this time domain is:

$$\bar{d}_1 = \frac{\rho C}{\tau_{1D}} C_3$$

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

## 2.1 Experimental Material

The experimental material was FV520B martensitic precipitation-hardening stainless steel plate produced by alkaline electric furnace smelting followed by electroslag remelting. The main chemical composition (mass fraction, %) was: 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, Mo 1.3-1.8, Nb 0.25-0.45, P $\leq$ 0.025, S $\leq$ 0.03, with Fe as the balance. To improve machinability, the plates underwent heat treatment with the following process: (1) solution treatment at (1050\$$\pm$10)$^\circ Cfor1hfollowedbyaircooling;(2)intermediateadjustmentat(850\pm10)^\circ Cfor2hfollowedbyoilcooli$ for 3 h followed by air cooling. Tensile tests yielded an ultimate strength of $\sigma_b = 1095$ MPa and a yield limit of $\sigma_{0.2} = 1343$ MPa. Additionally, to accurately calculate 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. 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 surface temperature, a layer of black matte paint was sprayed on the specimen surface to enhance emissivity.

## 2.2 Experimental Method

In a stable laboratory environment, uniaxial sinusoidal cyclic loading tests were conducted on specimens using an MTS810 hydraulic servo testing machine. Tests employed stress control mode with a constant stress ratio $R = 0.1$. 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 only 0.02°C. To maintain relatively stable temperature boundary conditions, the testing machine grips were continuously cooled with circulating water, and a small fan provided unidirectional airflow over the loaded specimen surface to maintain a stable air flow field.

All experiments employed stepwise loading, with $1 \times 10^4$ cycles at each load level, followed by unloading and cooling to room temperature before the next level. The infrared thermal imager recorded 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 periods, the specimen reached thermal equilibrium with the environment and maintained relatively stable temperature. Specific loading procedures were as follows:

1. To investigate high-cycle fatigue damage under different stress amplitudes, a new specimen was subjected to stepwise graded loading at 10 Hz, starting at $\sigma_a = 230$ MPa and increasing by 10 MPa per level until the final level of $\sigma_a = 440$ MPa, as shown in [Figure 2a: see original paper].
2. To study loading sequence effects, a new specimen underwent seven sequences of graded loading at 10 Hz, with each sequence consisting of four levels at stress amplitudes of 300, 320, 380, and 400 MPa, as shown in [Figure 2b: see original paper].
3. To examine loading frequency effects, graded loading tests were conducted at 5, 7.5, 10, 12.5, 15, 17.5, and 20 Hz, with each test consisting of five levels at 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 at 10 Hz on two new specimens at stress amplitudes of 380 and 400 MPa, with pauses every $1 \times 10^4$ cycles for cooling to room temperature before resuming. The thermal imager recorded surface temperature during the 5 seconds before resuming and the 15 seconds before each pause.

## 3. Experimental Results and Analysis

Processing the acquired thermal data yielded the average temperature rise $\bar{\theta}(x)$ during the 15 seconds before termination of each loading level. Double exponential function regression analysis was then performed to determine the regression equation. Using parameters from this equation, the average intrinsic dissipation $\bar{d}_1$ during the 15 seconds before loading termination was obtained through simple calculation using equation (8), representing the material' s intrinsic dissipation under that condition.

[Figure 3: see original paper] shows the variation of intrinsic dissipation $\bar{d}_1$ for FV520B steel. The results demonstrate that intrinsic dissipation increases continuously with stress amplitude, with a noticeable inflection occurring near $\sigma_a = 360$ MPa. The data pairs $(\sigma_a, \bar{d}_1)$ were divided into two regions and linearly fitted separately. The intersection of the two fitted lines determines the inflection point, corresponding to a stress amplitude of 357.48 MPa, which represents the material’ s fatigue limit $\sigma_0$.

The slopes of the upper and lower fitted lines are 635.21 and 2436.59, respectively—nearly a fourfold difference. This phenomenon indicates a transition in the generation mechanism of intrinsic dissipation at the inflection point, corresponding to a change in microstructure motion mechanisms. Analysis based on the Granato-Lücke dislocation pinning model and Frank-Read dislocation multiplication theory reveals that FV520B steel’ s microstructure contains both weak pinning points (solute atoms, vacancies) and strong pinning points (second phases, dislocation tangles, grain boundaries). 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 lines is proportional to intrinsic dissipation. Notably, this oscillation is reversible and does not cause substantive changes in dislocation structure; dislocations return to their initial positions after stress unloading, resulting in no fatigue damage.

Above the inflection point, dislocation lines deviate far from their equilibrium positions, creating 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 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 solely reversible microstructural motion (dislocation oscillation between strong pinning points) to combined reversible and irreversible motion (permanent slip, strong pinning point unpinning, and dislocation multiplication). The stress amplitude at this inflection point is precisely the material’ s fatigue limit.

Additionally, [Figure 3: see original paper] shows a good linear relationship between stress amplitude and intrinsic dissipation below the fatigue limit, where intrinsic dissipation should be entirely caused by reversible microstructural motion. Assuming this linear relationship remains valid above the fatigue limit, the data obtained by extrapolation can be subtracted from experimental data to calculate the portion of intrinsic dissipation caused by irreversible microstructural evolution at stress amplitudes above the fatigue limit (360–440 MPa), 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 microstructural evolution proceeds at a relatively constant rate under constant stress amplitude. The damage evolution process during high-cycle fatigue can be quantitatively characterized by the accumulation of the intrinsic dissipation portion related to irreversible microstructural changes. Fatigue failure occurs when this accumulated amount reaches a critical value $E_c$, which is a material constant independent of loading history.

Using data from [Figure 4: see original paper] for stress amplitudes of 380 and 400 MPa, the accumulated intrinsic dissipation related to irreversible microstructural evolution throughout the fatigue life—the critical value for fatigue failure—can be obtained. Comparison of the critical values from these two stress amplitudes shows little difference ($1.3149 \times 10^{10}$ and $1.2901 \times 10^{10}$ J/m$^3$), partially validating the previous assumption regarding calculation of intrinsic dissipation caused by reversible motion above the fatigue limit. To reduce error, the average value of $1.3025 \times 10^{10}$ J/m$^3$ was taken as the actual fatigue failure critical value $E_c$ for the material. Combining this with data from [Figure 4: see original paper], the fatigue life $N_f$ at each stress amplitude can be calculated. Using the least squares method, the stress-life curve (S-N curve) at 50% survival probability was determined by linear fitting of data pairs $(\sigma_a, N_f)$ in double logarithmic coordinates, as shown in [Figure 6: see original paper].

[Figure 7: see original paper] shows results from seven groups of graded loading tests on a single specimen. The results indicate no significant differences in intrinsic dissipation at the same stress amplitude across different loading sequences, demonstrating that high-cycle fatigue damage in FV520B steel is independent of loading sequence. In other words, the damage evolution rate is determined solely by stress amplitude and is independent of loading history. This also validates the reasonableness of using a single specimen to measure intrinsic dissipation at different stress amplitudes. Furthermore, according to the Granato-Lücke dislocation pinning model, intrinsic dissipation at 300 and 320 MPa should be caused by 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 results from graded loading tests at different frequencies. The results show that at the same stress amplitude, intrinsic dissipation of FV520B steel increases continuously with loading frequency, maintaining an essentially proportional relationship. This indicates that fatigue damage per cycle is constant and independent of loading frequency. Therefore, it can be inferred that within the frequency range investigated, the fatigue life of FV520B steel is determined only by stress amplitude and is unaffected 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 microstructural evolution during high-cycle fatigue has clear physical signif-

icance.

2. FV520B steel exhibits a relatively stable damage evolution rate under constant alternating stress amplitude, with the rate determined by stress amplitude and independent of loading sequence. Fatigue damage per loading cycle is also unaffected by loading frequency. When the accumulated intrinsic dissipation related to irreversible microstructural evolution reaches a critical value during fatigue, the material fails, 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.*