Review

A Review of Fatigue Limit Assessment Using the Thermography-Based Method

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Abstract: Fatigue limit assessment methodologies based on the thermography technique are comprehensively studied in this work. Three fundamental indicators pertaining to temperature increase, intrinsic energy dissipation, and thermodynamic entropy are discussed in sequence. The main train of thought of thermo-based research is outlined. The main objective of this paper is, on the one hand, to describe some works that have been accomplished in this field and, on the other hand, to present further potential for future studies involving fatigue behaviors and thermography approaches.

Keywords: thermography; fatigue limit; energy dissipation; thermodynamic entropy

1. Introduction

Fatigue performance is one of the most important mechanical properties of mechanical structural parts and components [1,2]. Components and parts made of metallic and non-metallic materials are prone to be subject to cyclic loads, and fatigue cracks form at the location where stress concentration is more prominent [3]. However, fatigue cracking is often imminent and unpredictable, and therefore, there are typically no obvious indicators of upcoming fatigue fracture. Finally, mechanical structures may suffer greatly from unexpected fatigue-fractured components, which can result in large financial losses and, in some cases, fatalities [4]. Statistics data show that fatigue failure is responsible for over 90% of metallic structural failure accidents [5]. Therefore, to quickly and accurately estimate the fatigue performance of mechanical structural components, the scientific and industrial sectors must implement a fair, efficient, and scientific fatigue evaluation of mechanical components.

Wöhler, a German engineer in the 19th century, pioneered systematic examination of railway wheel axle fatigue life under cyclic loadings [6]. This investigation revealed that even at stresses far lower than static yield strength, metallic materials are still susceptible to fatigue fracture. Furthermore, the specific loading circumstances have an obvious influence on the capacity of metallic materials to withstand alternating cyclic load cycles. From the point of view of terminology, the diagram that shows the number of cycles to failure of specimens undergoing the same stresses but with various stress levels is referred to as Wöhler-curves or S–N curves, where S and N stand for stress and the number of cycles to failure, respectively. Since then, scholars and engineers have devoted considerable work throughout the past two centuries to attain an enhanced understanding of fatigue while developing standards and codes to elevate the fatigue resistance of mechanical
components. This has led to increases in a plethora of information and expertise in grasping fatigue methodologies [7,8] and devising anti-fatigue solutions [9].

Currently, the two main areas of the evaluation of the fatigue performance of materials or structures are as follows [10]: (1) combining the service status of in-service structures with statistical methods and cumulative damage theory to predict the fatigue strength of components while taking into account the influence of various factors on fatigue performance, and (2) evaluating the safe fatigue life based on the S–N curve in conjunction with statistical methods and cumulative damage theory. The progressive evolution of these works has established a research basis for comprehending the mechanism of structural fatigue failure and given strong theoretical backing for further study of fatigue assessment.

In the past two decades, with the widespread application of infrared thermography techniques in the field of fatigue assessment, it has become feasible to establish a fatigue assessment method combined with the advantages of fast and physical essence [11–13]. As a result, scholars have achieved a great deal of progress in this area, progressively developing a study strategy that centers on temperature rise evolution [14]. The temperature increase evolution includes three phases (see Figure 1): (i) rapid increase within limited cycles in Phase I; (ii) stabilized temperature increment, which accounts for ~90% cycles of the whole cycles; (iii) final temperature rise when macro-cracks have formed in Phase III. The related works of fatigue evaluation, e.g., fatigue life [11,15–20] and fatigue limit [21–25], based on the temperature indicators corresponding to temperature rise slope and stabilized temperature increment, are well reported.

Figure 1. The typical temperature increase evolution with the increasing number of cycles. Reprinted with permission from ref. [26], 2021, Elsevier.

Fatigue is a process that involves continuous energy dissipation, most of which is converted into heat in the macroscopic state and manifests as the temperature rise evolution of the material surface [27,28]. The heat dissipation within the macroscopic scale is associated with internal microstructure change. These microstructural changes often happen in the region where the stress concentration, such as grain boundaries, dislocations, vacancies, and other defects, occurs [29,30]. Thus, the main objective in this field is to gain an understanding of the relationship between fatigue behaviors and energy dissipation, realizing a rapid fatigue evaluation, including fatigue life [8,31–34] and fatigue limit, from the macroscopic scale level [33,35]. This has motivated scholars to examine the correlation between energy dissipation and the motion of the internal microstructure of materials.

Energy dissipation during the fatigue process induces a gradual increase in disorder and damage evolution within the material, which is accompanied by an increase in thermodynamic entropy [36]. The fatigue fracture happens when the accumulated entropy generation reaches a critical threshold. Therefore, using entropy to estimate fatigue behaviors has a more profound physical meaning compared with pure temperature index and energy dissipation parameters [37]. However, even with a lot of work completed, a thorough review of infrared thermography techniques is still needed. Despite the review by Teng et al. [5] and Mohammad et al. [38] having advanced the understanding of the thermodynamic framework, criteria for determining fatigue limit based on threshold or
bi-linear approaches have not yet been discussed. Furthermore, the discussion and further perspectives on the fatigue limit determination based on the non-linear response relationship have not been well addressed.

The present paper provides an in-depth review of several thermo-based fatigue evaluation studies with an explanation of the corresponding theoretical foundation, phenomenological perspective, and experimental approaches. This article solely reviews the assessment of fatigue limits based on infrared thermography due to space limitations. Thermodynamic rules, in particular the inherent energy dissipation and entropy, which are crucial in predicting the fatigue threshold or fatigue strength, will receive specific attention. Section 2 introduces three fatigue limit evaluation approaches with the support of temperature rise, intrinsic dissipation, and thermodynamic entropy. The prospects regarding the thermo-based investigations are presented in Section 3, and some concluding remarks are presented in Section 4.

2. Fatigue Limit Evaluation Methods

Determining the fatigue limit and S–N curve of materials requires careful evaluation of their fatigue properties. Numerous engineering approaches for evaluating fatigue parameters, such as the staircase method for fatigue limit assessment and stress-based or strain-based for fatigue life evaluation, are often used in the field of fatigue investigation. In recent years, infrared thermography has provided a new method for fatigue assessment from a thermodynamic perspective. The process of fatigue is an irreversible thermodynamic process followed by a temperature rise response. Thus, the focus of this section and the ones that follow will be on thermo-based techniques for evaluating fatigue limits.

2.1. Temperature-Based Methods

The typical temperature rise evolution can be divided into three stages [29], as shown in Figure 1. The first stage is characterized by a rapid increase in temperature over a short time; the second stage, which lasts for 90% of the fatigue life of some metallic or composite materials under constant stress amplitude, is marked by a tendency for the temperature to stabilize; and the third stage is characterized by a sharp increase in temperature along with rapid crack propagation.

2.1.1. Stabilized Temperature Increment

As pioneer researchers in the field of thermo-based methods, La Rosa and Risitano [39] and Luong [13] were the first to utilize bilinear fitting to determine the fatigue limit of the related materials after observing the clear double slope characteristics associated with temperature increase response of metal materials at different stress amplitude levels. Crupi proposed a two-stage quantitative relationship when the stress amplitude is within the lower and higher ranges [40]:

\[
\Delta T_{\text{stab}} = \begin{cases} 
0, & \sigma_a < \sigma_f \\
\alpha \sigma_a^2 + \beta, & \sigma_a > \sigma_f
\end{cases}
\]

(1)

where \( \Delta T_{\text{stab}} \) denotes the stabilized temperature rise increment during the fatigue process, \( \sigma_a \) shows the subjected stress amplitude, and \( \sigma_f \) represents the fatigue limit.

Subsequently, relevant researchers also conducted research on the temperature rise response of different materials [16,22,24,41–46] and reached the following conclusion: (1) the material’s stable temperature rise increases with the increase in the load level; (2) there is a small drop in temperature rise at the first and second stage turning points, which is associated with the material hardening [26,47].

Mostofizadeh et al. [48] described a procedure for fitting and calculating the fatigue limit, and this method was also used for the determination of C45 steel and additively-manufacture 316L stainless steel specimens by Pirinu et al. [25] and Balit et al. [49]. The
fatigue limit is defined as the intersection of the abscissa and the fitting line of the data with the much bigger temperature increase increment, as shown in Figure 2.

![Figure 2](image)

**Figure 2.** The proposed fatigue limit prediction method is based on the stabilized temperature rise.

Bayati et al. [50] plotted the self-heating curve of a virgin and a pre-strained sample of SLM-fabricated NiTi alloys by a zero-dimensional (0D) approach (see Figure 3). This approach assumes that the temperature field within the gauge remains homogenous, and therefore, the stabilized temperature rise can be calculated by avoiding the additional heat generation from upper and lower grips. The 0D approach calculation formula is shown in Equation (2) [50]:

\[
\theta^{0D} = T_{\text{specimen}} - \frac{T_{\text{uppergrip}} - T_{\text{lowergrip}}}{2}
\]

(2)

where \( \theta^{0D} \) shows the temperature increment of the specimen center, \( T_{\text{specimen}} \) denotes the temperature value of the specimen center, and \( T_{\text{uppergrip}} \) and \( T_{\text{lowergrip}} \) are the reference temperatures at the upper and lower grips, respectively.

![Figure 3](image)

**Figure 3.** The fatigue limit estimation of the virgin and pre-strained sample of SLM-fabricated NiTi alloys, reprinted with permission from ref. [50], 2020, Elsevier.

Louge et al. [33] introduced the RVE model to analyze the temperature rise response mechanism of the fatigue process. To facilitate analysis, the specimens during the fatigue process are divided into elastic-plastic matrix and elastic-plastic inclusions. The model suggests that two mechanisms, namely anelasticity and microplasticity, are responsible for stabilized temperature rise response with the gradually increased stress amplitude levels, as shown in Equation (3) [33]. Anelasticity is the primary contributor to the stabilized rise increment when the stress amplitude is below the fatigue limit, and within this stage, the microstructure evolution mechanism is recoverable. No more sites within the elastoplastic matrix are activated in this process, inducing a mild temperature rise. However, irreversible microplasticity inside the elastic-plastic matrix gradually activates when the stress amplitude is above the fatigue limit, resulting in a sudden rise in temperature, as illustrated in Figure 4. Combined with Equation (3), it is much easier to understand the physical meaning of Figure 4. When the stress amplitude is within a lower range, only
first part corresponds to temperature rise. While when the stress amplitude beyond the endurance limit, both first and second parts contribute the stabilized temperature rise.

$$\bar{\theta} = \alpha \left( \frac{\Sigma_0}{\Sigma_{0,\text{max}}} \right)^2 + \beta \left( \frac{\Sigma_0}{\Sigma_{0,\text{max}}} \right)^{m+2}$$  \hspace{1cm} (3)

**Figure 4.** Temperature rise mechanism interpreted by the microstructure movement corresponding to the RVE model, reprinted with permission from ref. [51], 2022, Elsevier.

Saint-Sulpice et al. [51] developed a probabilistic two-scale model for determining the self-heating curve of NiTi Shape Memory Alloys under different cyclic stress levels, as illustrated in Figure 5. The non-linear self-heating curve is connected with the fatigue performance, and the fatigue limit was predicted in a short time by the presented model, as shown in Equation (4) [51] and Figure 5b.

$$\overline{\Sigma_{\text{mod}}} = \int_0^\infty \Sigma_{\text{max}} \frac{dP_F}{d\Sigma_{\text{max}}} d\Sigma_{\text{max}}$$

$$= S_0 \left( \frac{V_0}{V_{\text{eff}}} \right)^{\frac{1}{m}} \Gamma \left( 1 + \frac{1}{m} \right)$$  \hspace{1cm} (4)

**Figure 5.** Rapid estimation of the fatigue limit of the superelastic NiTi Shape Memory Alloys: (a) RVE model; (b) fatigue limit estimated by self-heating method, reprinted with permission from ref. [51], 2022, Elsevier.
More recently, Bustos et al. [52] developed a new standard for the measure of the temperature increment in Phase II. The experimental data of temperature vs. stress amplitude were performed under a successive increasing loading with a constant increase increment of stress amplitude, as illustrated in Figure 6a. The experimental data associated with Phase I and II are fitted to avoid the influence of the scatter of the data, as shown in Figure 6b. Based on the obtained temperature increment under different stress amplitudes, the experimental data on temperature increment under high and low varying stress amplitudes are, therefore, grouped. Finally, data from both high and low groups are fitted, respectively, and the fatigue limit, namely, the intersection of these two groups, is determined. The schematic of this approach is shown in Figure 6.

![Figure 6](image-url1)

**Figure 6.** The fatigue limit determination procedure is based on the thermography method, reprinted with permission from ref. [52], 2022, Elsevier. (a) The step procedure for the measurement of temperature rise with the increasing stress levels; (b) Fitted curve of the temperature rise in Phase I and II; (c) Fitted curve of the temperature rise vs. stress amplitude.

2.1.2. Initial Temperature Rise Slope

Mehdizadeh et al. [53] measured the fatigue temperature rise process of 304 stainless steel and 1018 steel by building an infrared thermal image testing platform. They observed that there was an obvious connection between the load level and the slope of temperature increase in Phase I (see Figure 7). As a result, they proposed a method for determining the fatigue limit based on the initial slope of temperature rise. The equation used to calculate this temperature increase slope is displayed in Equation (5) [53]:

$$R_\theta = -m(\theta_i - n)$$

![Figure 7](image-url2)

**Figure 7.** The schematic of the initial temperature rise slope regarding the three-stage temperature rise evolution, reprinted with permission from ref. [53], 2018, Elsevier.
Colombo et al. [54] performed fatigue tests of both undamaged and artificially damaged samples of composite materials with increasing stress levels, and the temperature rise response under different stress levels was detected by the IR-thermography technique. The relationship between the change in temperature increment versus cycles within Phase I and stress amplitude was plotted, and therefore, the fatigue limit was estimated by using the typical bi-linear method. The prediction outcome by the developed method is illustrated in Figure 8.

![Figure 8](image)

**Figure 8.** The fatigue limit estimation outcome using the thermography-based method: S-type shows the undamaged specimen, T-type shows the specimen with a delamination in the middle location, U-type denotes the specimen with a delamination in the upper part, reprinted with permission from ref. [54], 2019, Elsevier.

### 2.1.3. Harmonic Methods

The thermoelastic effect, resulting in a temperature variation at the identical loading frequency, is the sole heat source engaged once a metallic material is repeatedly loaded inside an elastic field under adiabatic circumstances [55]. This temperature rise process, induced by the thermoelastic effect, is called the first harmonic. However, some heat sources related to irreversible energy dissipation instantly occur when heat dissipation and non-reversible microplasticity occur. Within this point, more harmonics indices, i.e., first and second harmonics, emerge as a result of the continued formation of heat dissipation in every cycle, followed by the thermoelastic equation eventually losing its ability to accurately describe temperature variations. The harmonic models were proposed by Krapez et al. [56] and Bremond and Potet [57], and hereinafter, this approach was implemented for fatigue assessment by scholars in the field of thermography fatigue [58–61].

More recently, the fatigue limit predictions using global and local methods based on first and second harmonic amplitudes were compared [55]. Two stress ratios are considered in this work. The results showed that both global and local methods based on the second harmonic (SH) amplitude exhibit an ideal quintessential bi-linear trend, as shown in Figure 9. The fatigue limit values with an R of 0.1 and -1 are within the range of 300–310 MPa and 210–230 MPa, displaying a reasonable dispersion band. This seems to imply that the second harmonic correlates with the fatigue or endurance limit of materials. In contrast, the turning point, corresponding to the optimal bi-linear trend, is not observed, indicating a weak capacity for fatigue limit estimation. More details can be found in ref. [55].
Figure 9. The response relationship between second harmonic (red dot) and stress amplitude with a stress ratio of 0.1 and −1: (a) \( R = 0.1 \), global method; (b) \( R = 0.1 \), local method; (c) \( R = -1 \), global method; (d) \( R = -1 \), local method, reprinted with permission from ref. [55], 2022, Elsevier.

2.2. Energy-Based Methods

The temperature increase response during fatigue is a macroscopic manifestation of its energy dissipation to the exterior. Based on the temperature increase response, along with the thermal physical properties of the material, the physical connotation of fatigue may be deeply revealed from the perspective of energy dissipation.

2.2.1. Energy Model Based on the Stabilized Temperature

Guo et al. [62] proposed an intrinsic dissipation for fatigue limit prediction and reported that intrinsic dissipation is much more sensitive to changes in microstructure. Two microstructure evolution mechanisms are considered to be associated with dissipated energy, i.e., elastic internal friction and microplastic deformation. When the alternating stress amplitude is lower than the fatigue limit value, the dissipated energy is induced by internal friction, which does not lead to fatigue damage. While the stress is higher than the fatigue limit, both internal friction and microplasticity induce intrinsic dissipation, and microplasticity is related to damage accumulation. The fatigue limit evaluation model is summarized in Equation (6) [62] and Figure 10:

\[
\begin{align*}
    d_{ij} &= a \sigma_{ij} + b \quad (\sigma_{ij} \leq \sigma_0) \\
    d_{ij} &= A \sigma_{ij} + B \quad (\sigma_{ij} > \sigma_0)
\end{align*}
\]

where \( d_{ij} \) shows the intrinsic dissipation of the specimen, \( \sigma_{ij} \) applied denotes the stress amplitude, and \( \sigma_0 \) represents the fatigue limit. Moreover, \( a, b, A, \) and \( B \) are the material-related coefficients.
Fan et al. [63] proposed a unified energy dissipation model for the evaluation of the behaviors of metallic materials, and this model was also employed by Teng et al. [64]. In this model, energy dissipation serves as a fundamental indicator for evaluating fatigue damage. The functional correlation between macro and micro fatigue stress states and energy dissipation is expressed as [63]:

\[
    d_i = \begin{cases} 
    Af_i \sigma_y (\Sigma_a - \sigma_y) & \Sigma_a > \sigma_y = \Sigma_f \\
    0 & \Sigma_a < \sigma_y = \Sigma_f 
    \end{cases}
\]  

(7)

where \(d_i\) is the energy dissipation, \(\sigma_y\) is yield stress within the microscopic scale, which is equivalent to the fatigue limit within the macroscopic scale, \(\Sigma_a\) denotes the stress amplitude, \(A\) is a coefficient corresponding to materials, and \(f_i\) is the test frequency.

Haghshenas et al. [65] proved that the presence of internal friction cannot be ignored in a low-cycle fatigue regime (LCF). Internal friction that corresponds to both damaging and non-damaging fatigue behaviors causes energy dissipation when the stress amplitude exceeds the fatigue limit. As a result, they put forward an approach that uses the measurement of metallic materials’ damping values under various stress scenarios to determine the fatigue threshold of certain materials, as illustrated in Figure 11.

Yang et al. [66] proposed a two-scale energy dissipation model by introducing the Representative Volume Element (RVE) model. In this model, the dissipated energy with the increasing stress level is taken into account as a non-linear trend, and the dissipated energy is induced by both anelastic and microplastic microstructure motions. The relationship between stress amplitude and energy dissipation can be defined as Equation (8) [66]:
\[
d_i = \begin{cases} 
d_i^{an} + d_i^{in} = A\sigma_a^m + B(\sigma_a - \sigma_\infty)^m & \sigma_a > \sigma_\infty \\
d_i^{an} = A\sigma_a^2 & \sigma_a < \sigma_\infty \end{cases}
\]

where \(d_i^{an}\) and \(d_i^{in}\) show the anelastic dissipation and microplastic dissipation, respectively. \(\sigma_a\) and \(\sigma_\infty\) denote the stress amplitude and fatigue limit, and \(A\) and \(B\) are material-related coefficients.

Wei et al. [32] derived a local heat conduction equation for the butt joint specimen, as shown in Equation (9), and the obtained equation follows some assumptions:

- \(\rho, C,\) and \(k\) are not influenced by the self-heating effect;
- The thermoelastic effect does not induce the stabilized temperature increment;
- The coupling heat source and external heat source do not need to be considered.

\[
\rho C \left( \frac{\partial \theta}{\partial t} + \frac{\theta}{\tau_{eq}} \right) = d_i
\]

where \(\theta\) and \(\tau_{eq}\) is the stable temperature increment in Phase II and characteristic time corresponding to external surroundings. Due to the rate of temperature change asymptotes to be zero, Equation (9) is rewritten as:

\[
d_{cycle} = \rho C \frac{\theta}{f_i \tau_{eq}}
\]

where \(f\) denotes the frequency of fatigue tests. The representative volume element (RVE) model, as shown in Figure 12, was used to correlate the energy response and fatigue behaviors within the macro- and micro-scales. The threshold stress, i.e., yield stress within the microscopic scale, which corresponds to irreversible atom activation within the elastoplastic inclusion, is considered the fatigue limit. The relationship between dissipated energy and stress amplitude level is shown in Equation (11) [32].

**Figure 12.** The mechanism explanation of the microstructure evolution with successive stress amplitude levels behind the self-heating process by representative volume element model, reprinted with permission from ref. [32], 2023, Elsevier. (a) The schematic of Representative volume element model; (b) The activated atoms with the RVE region with the increase in stress amplitude.

\[
d_{cycle} = \begin{cases} 
d_{an} = s_1(\Sigma_a - \Sigma_f) + d_f \quad (\Sigma_a < \Sigma_f) \\
d_{an} + d_{in} = s_2(\Sigma_a - \Sigma_f) + d_f \quad (\Sigma_a > \Sigma_f) \end{cases}
\]

where \(d_{cycle}\) denotes the dissipated energy per unit cycle, \(d_{an}\) represents the dissipated energy corresponding to non-damaging internal friction, \(d_{in}\) symbolizes the energy dissipation induced by non-recoverable microplastic behaviors, and \(d_f\) is the energy dissipation related to the critical stress, i.e., fatigue limit. Moreover, \(\Sigma_a\) and \(\Sigma_f\) correspond to the macro-stress amplitude and macro-fatigue limit, respectively.
Li et al. [67] presented an expression of the one-dimensional distribution of the temperature rise along the gauge section of a carbon fiber-reinforced polyether-ketone (CFRP) specimen. The temperature distribution is written as Equation (12) [67], and the temperature distribution is shown in Figure 13.

\[
\theta(x, i) = C_1(i)e^{rx} + C_2(i)e^{-rx} + C_3(i)
\]  

(12)

where \( \theta \) is the mean temperature value along the axial direction of the specimen, and \( x \) is the length of the gauge part. Furthermore, \( C_1 \) and \( C_2 \) are temperature boundary-dependent coefficients, \( C_3 \) relates to intrinsic dissipation, and \( r \) corresponds to the thermal loss on the surface of the sample.

![Figure 13](image)

Figure 13. The self-heating response under different load levels of carbon fiber reinforced polyether-ketone: (a) The stabilized temperature rise increment (red triangles) with successive cyclic loads; (b) The temperature distribution of CFRP specimen along the axial gauge section, reprinted with permission from ref. [67], 2021, Elsevier.

By solving Equation (12) through an exponential regression approach and in combination with the heat balance equation, i.e., Equation (9), the intrinsic dissipation calculation formula is expressed as [67]:

\[
d_i(i) = \lambda r^2 C_i(i)
\]  

(13)

where \( d_i(i) \) means the intrinsic dissipation per unit time. Therefore, the fatigue limit was determined, as shown in Figure 14, by using the calculated data from Equation (13).

![Figure 14](image)

Figure 14. The prediction value of the endurance limit of CFRP by intrinsic dissipation data from Equation (13), reprinted with permission from ref. [67], 2021, Elsevier.

More recently, the one-dimensional temperature distribution in Phase II of laser powder bed fused 304 L steel specimens was investigated by Zhang et al. [68] using double exponential regression curves. On this basis, the intrinsic dissipation under different stress amplitude blocks was estimated by employing Equation (13), and thus, the fatigue limit
was predicted in a short time, as shown in Figure 15. In addition, this method was also applied in the determination of the fatigue limit of S235JR steel [69].

![Fatigue life data](image)

**Figure 15.** Rapid fatigue limit evaluation of laser powder bed fused 304 L steel specimens based on intrinsic dissipation, reprinted with permission from ref. [68], 2023, Elsevier. (a) As-built specimens; (b) annealed specimens.

#### 2.2.2. Energy Model Based on the Initial Temperature Rise Slope

Jang et al. [70] estimated the energy dissipation of FV520B stainless steels collected from Guo et al. [62] using the initial temperature rise slope, and the fatigue limit was assessed based on the typical bi-linear fitting, as shown in Figure 16. Two microstructure evolution mechanisms were taken into account during this self-heating process. When the stress amplitude is below the endurance limit, the dissipated energy is considered to be induced by the internal friction corresponding to anelastic behaviors. However, the energy dissipation was caused by both internal friction and microplastic deformation when the stress amplitude is higher than the fatigue limit.

![Energy dissipation response](image)

**Figure 16.** The energy dissipation response with the successive load levels and fatigue limit evaluation, reprinted with permission from ref. [70], 2018, Elsevier.

Nourian et al. [71] calculated the dissipated energy of FV520B stainless steels and Al 7075-T6 alloys using the initial temperature rise slope, and it can be expressed as Equation (14) [71]:

\[
\dot{Q} = \rho c R_0 = \rho c \frac{dT}{dr} \bigg|_{r=0} 
\]

Nourian considered that the dissipated energy during a high-cycle fatigue regime has a non-linear relationship with stress amplitude. The dissipated energy per unit of time \( Q \) has a quadratic power relationship with stress amplitude level within a lower stress range. The dissipated energy under this stress amplitude range is associated with recoverable internal friction. When the stress amplitude in a higher level, the energy dissipation is caused by both recoverable internal friction and irreversible microplastic deformations. Therefore, the energy dissipation under different stress amplitude ranges can be defined as Equation (15) [71]:

\[
\dot{Q} = \rho c R_0 = \rho c \frac{dT}{dr} \bigg|_{r=0} 
\]
\[ Q = \begin{cases} A\sigma_a^2 & (\sigma_a \leq \sigma_f) \\ A\sigma_a^2 + B\sigma_a^\beta & (\sigma_a > \sigma_f) \end{cases} \]  

(15)

where \( A\sigma_a^2 \) and \( B\sigma_a^\beta \) correspond to recoverable and non-recoverable dissipated energies, respectively. \( A \) and \( B \) are proportional coefficients corresponding to recoverable and non-recoverable mechanical behaviors. The fitting result of experimental data of FV520B stainless steels and Al7075-T6 alloys are shown in Figure 17.

Figure 17. The fatigue limit determination of FV520B stainless steels (a) and Al7075-T6 alloys (b) based on Equation (15), reprinted with permission from ref. [71], 2021, Elsevier.

2.2.3. The Energy Model Based on a Sudden Stop of Temperature Rise in Phase II

Determining the intrinsic dissipation during the steady temperature increase stage in Guo’s model [62] and Li’s model [67] requires numerous complicated formula deductions and non-linear fitting. Meneghetti et al. [72–75] introduced a cool process during Phase II for calculating energy dissipation, and the calculation method was used to determine the dissipated energy of FV520B stainless steel by Yang et al. [76], as shown in Figure 18.

Figure 18. The sudden temperature stop in Phase II of FV520B stainless steel, reprinted with permission from ref. [76], 2020, Springer.

Huang et al. [77] carried out the sudden stop test during the self-heating process in Phase II, and the cooling curve after a stabilized temperature rise evolution under different cyclic loads was plotted in Figure 19a. On this basis, the generated heat dissipation per unit time of CFRP laminates with three stacking sequences was obtained, and therefore, the fatigue limit was evaluated by determining the dividing point between the mechanisms of internal friction and microplasticity damage. The predicted results are summarized in Figure 19b–d.
2.3. Entropy-Based Methods

From a thermodynamic standpoint, a rise in entropy suggests the depreciation and degradation of energy in addition to illuminating the direction of energy transmission and transformation. From a micro-statistical point of view, a rise in entropy has more profound physical implications as it suggests an increase in system disorder and damage. Fatigue is a thermodynamic process that is irreversible and involves energy dissipation and temperature-rising progress. This irreversible damage buildup process could be better described by employing entropy as the fundamental indicator for assessing fatigue performance, which takes full advantage of the benefits of the two physical quantities of energy and temperature.

The widespread agreement is that the behavior of the microstructural evolution of materials during fatigue processes is intimately linked to the generation of entropy. The two processes commonly attributed to the rise in entropy are elasticity and microplasticity. Fatigue damage is not caused by the entropy rise when the cyclic stress is modest since it originates from the internal friction of anelasticity. Both anelastic internal friction and microplasticity contribute to the entropy rise when the cyclic stress amplitude is significant, and fatigue damage is exacerbated by the microplasticity-caused entropy increase. Therefore, the fatigue limit of the material may be rapidly ascertained by measuring the intersection point between these two entropy-generating mechanisms.

Currently, there are three different ways to calculate entropy production, and these methods are primarily developed based on methods related to temperature rise and energy dissipation. The first method is based on the slope of the initial temperature rise [53,71,78,79], the second method is based on stable temperature rise [26,80], and the third method is based on the slope of the sudden temperature drop during stable temperature rise [77,81]. Three calculation approaches corresponding to thermodynamic entropy generation under constant cyclic loads are illustrated in Figure 20.

![Figure 19. Sudden cooling process in Phase II and fatigue limit prediction of CFRP laminates with different stacking sequences under different cyclic loads: (a) the cooling curve of [±45°]s stacking sequence; (b) the fatigue limit of [±45°]s based on Sudden cooling process, as well as the determination of [0°]s and [(0°/90°);(0°/(90°/0°)]; in (c,d), reprinted with permission from ref. [77], 2020, Elsevier.](image-url)
Figure 20. Three entropy generation calculations are based on three temperature-related standards: (a) initial temperature rise slope; (b) stable temperature rise increment; (c) sudden stop after stable rise process.

3. Discussion and Future Perspectives

3.1. Summarization of the Applicability of the Above-Mentioned Methods

It should be noted that the fatigue limit determination methods mentioned above, regardless of whether they rely on temperature data or more practically significant parameters like energy and entropy, are dependent on either the classical bilinear method or the threshold in the thermographic data versus stress amplitude. The material’s microstructural evolution information is implied by the clear intersection or threshold of the response of the thermographic data and stress amplitude. This detail reveals itself at the macroscopic level as an increase in surface temperature or energy evolution. It has significantly advanced the field of fatigue assessment research and established the groundwork for future studies that will yield faster and more precise fatigue assessments. Furthermore, it is important to note the following again:

(1) Whether it is the threshold-based approach or the bi-linear technique, the fatigue limit prediction method employed in the aforementioned research focuses on identifying the key turning point. However, there are no specific standards to accomplish this. Even though Huang et al., Wei et al., and Li et al. suggested a method for identifying boundary points based on the coefficient of determination, $R^2$, more research and confirmation are required. More details see Table 1.

(2) In many instances, a non-linear or linear non-linear two-stage characteristic is presented regarding the response relationship between infrared thermography data and stress amplitude levels. In Zhang’s work [68], for instance, the data are fitted using the bilinear approach; however, the coefficient of determination, $R^2$, is only around 0.8, which is less than the greater confidence, i.e., 0.95 or a higher value.

In summary, current research mainly focuses on linear behavior, and the determination of non-linear response relationship and fatigue limit may be the focus of future research.

Table 1. The summary of the above-mentioned fatigue limit prediction methods.

<table>
<thead>
<tr>
<th>Method</th>
<th>Indices</th>
<th>Determination of the Turning Point</th>
<th>Authors</th>
<th>Using the Standard of $R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature-based methods</td>
<td>Stabilized temperature increment</td>
<td>bi-linear</td>
<td>LaRosa and Risitano [38]</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Luong [13]</td>
<td></td>
</tr>
<tr>
<td>Stabilized temperature increment</td>
<td>non-linear threshold</td>
<td>Mostofizadeh et al. [47]</td>
<td></td>
<td>No</td>
</tr>
<tr>
<td>Initial temperature rise slope</td>
<td>bi-linear</td>
<td>Pirinu et al. [25]</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Balit et al. [48]</td>
<td></td>
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<td></td>
<td></td>
<td>Louge et al. [33]</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Mehdiizadeh et al. [52]</td>
<td></td>
<td>No</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Colombo et al. [53]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3.2. Future Perspectives

The paper provides a comprehensive review of fatigue limit evaluation using thermo-based methods for various materials, including metallic and composite materials, in combination with their welding connections. The central line of thermography fatigue investigations is outlined in the three main sections of this review, encompassing thermodynamics, energy dissipation, and temperature elevation response. In Section 2.1, the study utilizing temperature increment data for fatigue was first presented. In Section 2.2, an alternative energy dissipation model for determining the fatigue limit was examined. The quantitative relationship model between thermodynamic entropy generation and fatigue limit was then presented in Section 2.3. The discussion is summarized in Section 3.1. Herein, two aspects regarding the fatigue assessment using the infrared thermography can be focused in the future:

(1) **Fatigue Limit Prediction Aspect**

- The related study generally uses the bilinear approach to estimate a material’s fatigue limit by bilinear fitting; however, there is rarely any consistent standard for this slope turning point.
- One specimen can be used to estimate a material’s fatigue limit using the present thermal imaging approach, demonstrating this approach’s superiority in accurately predicting the fatigue limit. Nonetheless, for engineering applications, at least three specimens should be utilized to determine the fatigue limit, and the mean value should be determined together with the standard deviation because of the inaccuracies caused by the fitting and temperature-measuring processes.
• Currently, these approaches are mainly utilized at the level of metallic specimens within a laboratory scale, and the application of fatigue limit or strength prediction for metallic structures or components with intricate geometries has not been achieved for the time being. Moreover, the measurement of the temperature rise of metallic structures or components requires an accurate thermal emissivity, and applying a black coating on the surface of the corresponding structures is a big challenge.

• The previously mentioned study confined itself to examining the fatigue limit under certain load states, such as constant stress ratio and constant stress amplitude, with an emphasis on the rapid prediction of fatigue limits using the bilinear method. The prediction of material fatigue limit under various load instances, for instance, fluctuating stress amplitude or varying stress ratios, is not well investigated. Also, the effect of the initial condition of materials and environmental aspects on infrared thermography data is worth more study and examination in the future.

(2) *Fatigue Life Evaluation Aspect*

Owing to space limitations, this article only examines studies concerning the assessment of fatigue limits; however, precisely identifying fatigue limits serves as the foundation for assessing fatigue life. To provide a quick and precise evaluation of fatigue life, entropy generation or energy dissipation associated with damage are extracted, e.g., Mehdizadeh et al. [53,78], Wei et al. [26], Huang et al. [77], and Guo et al. [82], etc., based on the fatigue limit determination methodologies.

4. Conclusions

In this paper, the corresponding investigations concerning fatigue limit prediction based on three indicators, such as temperature increment, intrinsic energy dissipation, and thermodynamic entropy, are comprehensively reviewed. The primary framework behind these investigations, i.e., from temperature rise response to energy dissipation and entropy, is presented. The outcome of these studies encourages the significance of thermal imaging investigations in fatigue examination and indicates that the methodology may be a promising predictive method. Despite the large amount of work being done in this field, further investigation is necessary to validate the precision and dependability of thermobased approaches for confronting multiple aspects of the structural integrity problem owing to their unique characteristics.

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**Conflicts of Interest:** The authors declare no conflicts of interest.
Nomenclature

\( T_{\text{specimen}} \) The temperature value of specimen center

\( T_{\text{uppergrip}} \) The referenced temperature at the upper grip

\( T_{\text{lowergrip}} \) The referenced temperature at the lower grip

\( \Delta T_{\text{lab}} \) The temperature increment of the specimen

\( \theta^{0}, \theta, \theta \) The temperature rise in Phase II

\( \sigma, \sigma \) or \( \sigma_{d} \) Stress amplitude

\( \sigma_{f}, \sigma_{e}, \sigma_{y}, \Sigma, \Sigma_{\text{rad}} \) Fatigue limit or endurance limit

\( d_{f}^{n}, d_{m}^{n} \) or \( d_{n}^{m} \) Anelastic dissipated energy

\( d_{i}^{n}, d_{m}^{n} \) or \( d_{n}^{m} \) Inelastic dissipated energy

\( d_{1}, d_{i} \) Intrinsic energy dissipation

\( d_{\text{cycle}} \) Intrinsic energy dissipation per unit time

\( d_{l} \) Energy dissipation corresponding to fatigue limit

\( \Sigma_{0}, \Sigma_{0} \) or \( \Sigma_{r} \) Stress amplitude

\( \Sigma_{\max} \) Maximum stress within domain

\( \Sigma_{\text{rad}} \) Mean fatigue limit

\( f, f \) or \( f_{i} \) Experimental frequency

\( V_{0} \) Materials parameter

\( V_{\text{eff}} \) An effective volume for the explanation of stress inhomogeneity

\( S_{0} \) Materials parameter

\( R_{0} \) Initial slope of the temperature rise

\( \tau_{0q} \) Characteristic time corresponding to external surroundings

\( C_{1} \) Temperature-dependent coefficient

\( C_{2} \) Temperature-dependent coefficient

\( C_{3} \) Relates to energy dissipation

\( r \) Fitted coefficient

\( \lambda \) Fitted coefficient

\( \rho \) Density

\( C \) Specific heat

\( a \) Materials-related coefficient

\( b \) Materials-related coefficient

\( A \) Materials-related coefficient

\( B \) Materials-related coefficient

\( S_{1} \) Materials-related coefficient

\( S_{2} \) Materials-related coefficient

\( Q \) Intrinsic energy dissipation rate

\( \frac{\partial \Delta T}{\partial t} \) or \( \frac{d T}{d t} \) Initial slope of the temperature rise

\( \dot{\theta} \) Entropy generation rate

References


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