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Review on the Fatigue Temperature Evolution of Structural Metal

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Abstract: With the rapid development of infrared imaging technology in last decades, the application range of the nondestructive examination, including fatigue testing, is continuously wider. By reviewing the studies and utilizations of temperature evolution during metal undergoing cyclic loading, this paper provides a reference and also guidance for further research. According to the articles on fatigue temperature evolution, the present overview summarized general rule and characteristics of fatigue temperature evolution. The cause of this temperature evolution is specifically analyzed. Some fatigue life prediction methodologies based on the temperature evolution are systematically reviewed. Finally, a prospect of this research direction is given.

Key words: temperature evolution; infrared imaging; fatigue testing; nondestructive examination

1 Introduction

Dislocation movement in metals is the main cause of heat dissipation and consequently, rise in temperature [1-3]. Factually, for a wide range of metals subjected to deformation at moderate to high strain rate, almost all the plastic strain energy is converted into heat [4-5]. Particularly, Hodowany [6] claims that over a wide range of strain rates, almost 90% of the input plastic work converts into heat. It should be pointed out that for some metals with hexagonal close packed (hcp) structure such as zirconium and hafnium, a considerable fraction of plastic energy is not dissipated as heat, but stored in the material [5,7]. If the rate of heat generation is greater than the dissipation to the surroundings, the temperature of the specimen must necessarily increase. This kind of temperature increment can be used to determine the location of crack tip, predict the fatigue life and so forth. This phenomenon associated with fatigue degradation of material is concerned by more and more researchers.

2 Temperature evolution during the fatigue process

All fatigue processes are dissipative and irreversible, every cycle will release energy [8-10]. Most of the dissipated strain energy during fatigue test is converted into heat, which manifests itself in the form of changing temperature. This is a characteristic of metals experiencing hysteresis heating. The temperature evolution,

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however, is complicated and the associated data are hard to interpret. Complications arise only due to the interrelated effects of thermal and mechanical coupling, strain amplitudes, and loading histories, but also owing to multiple modes of heat transfer from the material to the environment [12]. Meneghetti [13] studied the fatigue limit of Stainless Steel specimen under uniaxial tests based on the experimental measurement of material thermal increment. He postulated that the energy dissipated in a unit volume of a material as heat seems to be a promising parameter for fatigue characterization. In fact, for a given material, loading and mechanical boundary conditions, the energy dissipated in a unit volume of a material depends only on the applied stress amplitude and load ratio undergoing a constant amplitude fatigue test.

Fargione et al. [14] used a thermographic technique to observe the evolution of surface temperature of specimens under fatigue load. In all of the tests performed, they observed that, with stress level above the fatigue limit σ_0, the thermal variation will be observable apparently. Figure 1 shows a typical evolution of the temperature plotted as a function of the number of cycles. It reveals that the temperature evolution undergoes three distinct phases: an initial increase (Phase I) followed by a steady-state (Phase II) and, then an abrupt increase prior to fracture (Phase III). Figure 1 illustrates the effect of elastic and plastic strain energies on the variation of the temperature of a body subjected to fatigue load. Plastic strain and its associated dissipation result in an increase in the average temperature while the material response to elastic strain is simply a cyclic change in temperature superimposed on the plastic response.

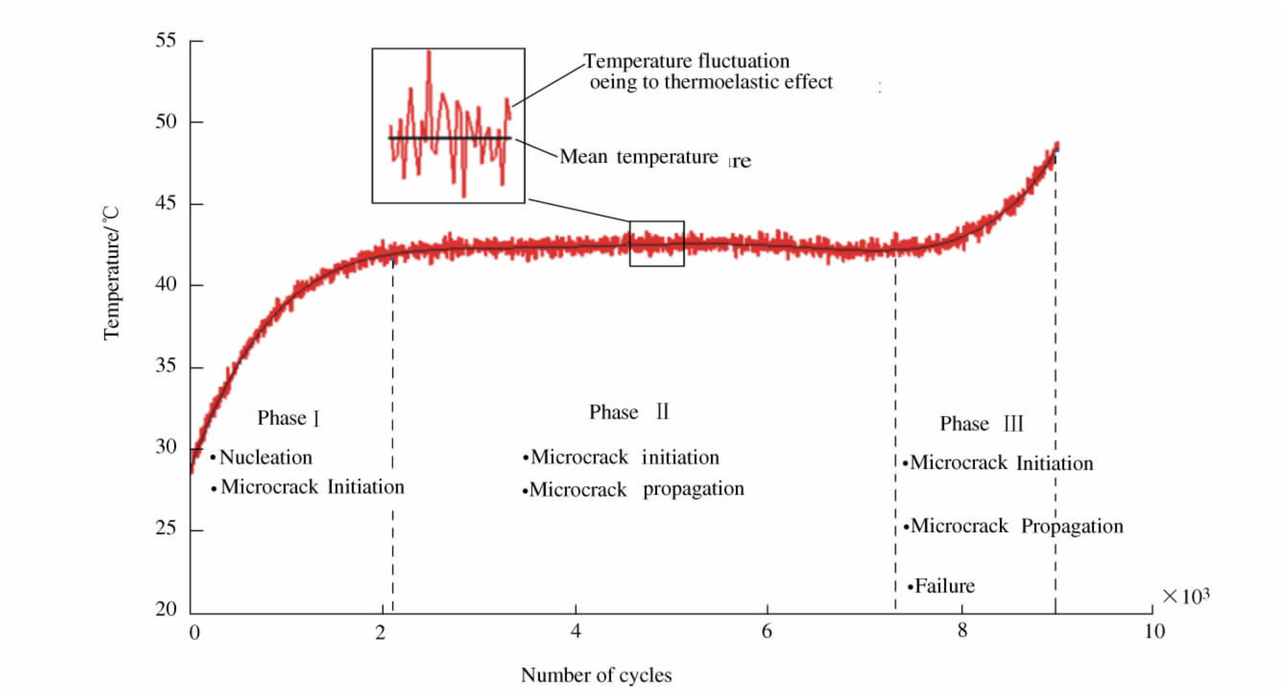

Figure 1 Typical temperature evolution during constant load

During the first phase, temperature drastically increases due to inelastic effect. Then, during equilibrium phase (Phase II) temperature slightly decreases due to the formation of new surfaces as a result of micro-cracks creation. Finally, temperature abruptly increases according to the large plastic deformation at the tip of the macro-crack.

The first phase of the temperature rise is limited to a very low number of cycles in general, about 10% of the entire lifespan of the specimen for loads not close to the yield stress [14]. The initial rise in temperature represents the material's response to the sudden movement of dislocations and defects accompanied with surface intrusion and extrusion [15-18]. Starting from the ambient, initially, the temperature rises since the energy generated is greater than the heat transferred out of the specimen. In this phase, the higher the displacement amplitude, the greater is the initial slope of temperature rise.

During the second phase, the cyclic stress and strain response becomes stable. As a result, there is a balance between the hysteresis-energy generation and heat dissipation as the mean temperature tends to a steady state. For loads that are greater than the fatigue limit, increasing the displacement results in an increase of the steady-state temperature in the second phase [14]. The second phase, i. e. , the period when the temperature tends to stabilize, varies considerably in the duration. For loads close to the yield stress, this phase is extremely short; while for loads that are only slightly above the fatigue limit σ_0, it extends over almost the whole lifespan of the specimen. It is worthwhile to mention that in this phase, a slight decrease in temperature can be observed in some cases. This can be attributed, in part, to heat loss to the surroundings [19] due to the creation of new surfaces as a result of micro-cracks formation [20]. Hence, in the process of heat balance between the hysteresis-energy generation and dissipation to the surroundings, the surface temperature of the specimen decreases slightly [19, 21].

In the third phase, the temperature rises rapidly after a comparatively small number of cycles until failure occurs. In this phase, macro-cracks are formed and the temperature suddenly rises due to large plastic deformation caused by stress concentrations at the crack tips, that is, the plastic work generated during this deformation is mostly converted to heat. Plastic deformation at the crack tip results in heterogeneity of temperature at the position where the specimen fractures [12, 22-23]. This sudden temperature rise could be used as a warning of an imminent fracture.

In view of the practical engineering needs and the difficulties in interpreting the details of energy transfer during fatigue, more researchers are focus on the relation between temperature evolution and the fatigue life. Many literatures showed that the temperature index has a correlation with fatigue life and can be utilized for the fatigue life prediction.

3 Temperature evolution-fatigue life prediction methodologies

These three phases of the temperature evolution has led researchers to develop various innovative ideas for establishing the relation between temperature and fatigue life. These temperature variations can be easily detected by infrared (IR) thermography technique as a function of time. Here, some representative works are listed.

Amiri et al [24-25] related the temperature evolution in the first phase to onset of fatigue failure. As shown in Figure 2, the thermal behavior of different materials-Aluminum 6061 and Stainless Steel 304 is presented when subjected to cyclic fatigue bending and torsion load. A fatigue criterion is proposed that relates the cycles to failure to the initial rate of temperature rise of tested materials.

$$N_f = c_1 R_\theta^{c_2} \tag{1}$$

Where N_f, c_1, R_θ, c_2 are the constants which are determined by tests.

Recently, Khonsari et al [26-27] developed this theory to estimate the remaining fatigue life and whether the material is intact (without loading history).

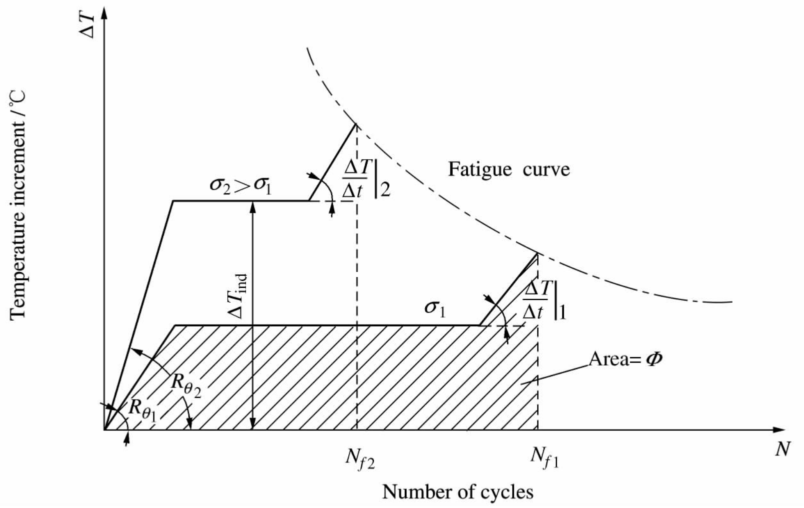

Figure 2 Explanatory diagram of temperature evolution-fatigue life prediction methodologies

Jiang et al [12] gained inspiration from the second phase, their papershowed that the difference between steady-state and ambient temperature can be correlated with the fatigue life (Figure 2). They reported the following relation between the fatigue life, N_f, and the temperature index, ΔT_{ind}, defined as the temperature difference between steady-state temperature and the temperature of the initial stress-free stage for an axially loaded specimen:

$$(N_f)^m = C\Delta T_{\text{ind}} \tag{2}$$

Where m and C are the material constants. Using this relationship, they recommend that the temperature during the steady-state condition can be used as a warning of impending failure.

Moreover, Risitano et al [14, 28-33] have also studied the second phase of temperature evolution for a long time and obtain many accomplishments. The Risitano method has proved effective in determining the fatigue limit of materials and their corresponding Wohler curves [14, 28]. The method begins with the observation that stress σ_i and increase in the surface temperature ΔT_{ind} of a loaded specimen (or mechanical component) are related (ΔT_{ind} could be considered directly proportional to the σ_i with respect to the fatigue limit

σ_0) for each load frequency f and stress ratio R. ΔT_{ind} is the stabilized temperature of the second phase (Figure 1) and for fixed R and f it is a practically constant for the entire test time. ΔT_{ind} depends on the maximum loading stress (Figure 2) (at a different value of ΔT_{ind} a different value of σ_i).

The third phase can be also related to fatigue life. Huang et al [34] showed the rate of temperature rise of the material with high ductility near the end of fatigue testing is related to the fatigue fracture. Their experimental results revealed that very close to the final failure there is a sharp increase in temperature (Figure 1) just after a steady-state condition. The temperature rise is associated with initiation and propagation of macrocrack [35] and imminent fracture; hence, this information can be used to terminate the operation of a machinery to prevent the catastrophic failure. The relation of the rate of temperature rise, ΔT, versus fatigue life was given as follows:

$$\frac{\Delta T}{\Delta t} = C' \cdot \exp\left(\frac{G}{(N_f)^{1/b}}\right) \tag{3}$$

Where t is the time and C', G and b are the constants depending on the material properties and the test conditions. Their data [34] indicated that a temperature rise can be detected at about 10 min prior to the fracture of a Stainless Steel (924) with high ductility and about 5 min for superalloy (GH33) with lower ductility. This could be used as a warning of an imminent fracture, thereby, the estimation of the time to failure provides the capability of shutting down the machinery before a catastrophic break down occurs.

Beyond these above-mentioned, some researchers are concentrating in the associating temperature evolution to fatigue life. Fargione et al [14] presented a procedure for analyzing the fatigue behavior of an axially loaded specimen based on the temperature evolution. They proposed that the integration of the area under the temperature rise over the entire number of cycles of a specimen remains constant, thus representing a basic characteristic of a given material:

$$\Phi = \int_0^{N_f} \Delta T \mathrm{d}N = \text{constant} \tag{4}$$

Where Φ is the constant regardless of the stress amplitude. Therefore, with a specified value of Φ for a given specimen or mechanical component, the entire fatigue curve can be obtained. In their study, the fatigue curve is defined as the locus of the tips of temperature profiles at the end of the tests. Recently, they found and also proved this relation, to some extent, like miner's rule, can be used to evaluate the damage condition of specimens [36].

It is easy to find that all these method of life prediction are all based on the researchers' view point. Their experiments just can support their own theories. However, whether these methods can be unified is a knotty problem. No doubt, unifying these models needs to not only integrate the formula, but also test more materials at different loading condition.

4 Conclusions

Temperature evolution during fatigue process and using this to predict the fatigue life are universally used in the estimation of fatigue damage, remaining life of structure and reliability, and many researchers pay much attention to them. In this paper, the whole fatigue temperature evolution and fatigue life prediction methodologies based on the temperature evolution were introduced. The present overview is intended to provide a basic guidance for understanding and utilizing the fundamental temperature variation during the fatigue process. How to integrate these methodologies into a unified theoretical system needs further study.

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