Fatigue damage indicators based on the infrared thermographic method

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Abstract It is a new and valuable research that studying the influence of heat treatments on fatigue performance of materials by the infrared thermographgic method. Based on three theoretical models of fatigue indicators, this paper studied mechanical properties of the virgin and heat-treated FV520B steels. With the three indicators and the energy theory, comparison analysis of macro-phenomenon and microstructure evolution during fatigue of the two type specimens was performed. Using the intrinsic dissipation, fatigue limits were fast determined. Influence of heat treatments on mechanical properties and fatigue life was discussed. The research shows that the accuracy of the lock-in thermography could satisfy the needs of engineering design.

Keywords Infrared thermographic method, Fatigue indicator, Heat treatment, Energy Approach

1. Introduction

Fatigue design requires statistical processing of numerous tests. However, the traditional evaluation methods are often difficult to be performed for their time-consuming and expensive costing[1,2]. The infrared thermographic method was first proposed by Risitano et al. [3] by using the surface temperature increments as the major fatigue indicator. The infrared thermographic method, based on the analysis of the heat during a loading fatigue test, was developed over the last 30 years. Fargione et al. [4] obtained the connection between the quantity of heat dissipated in taking a given element to failure based on the physical hypothesis, which the failure of materials through fatigue occurs when the energy of plastic deformation reaches a constant limiting value, and the fatigue limit by applying fatigue tests.

Suitable heat treatments can improve the static tensile strength and fatigue resistance of materials [5,6]. Now it is still a new task to investigate effect of heat treatments on fatigue behavior of materials using the infrared thermographic method. The purpose of this paper is to study the relationship between the internal microstructure and mechanical properties using different fatigue indicators. FV520B steel is a kind of martensite steel developed by Firth-Vickers Materials Lab in British. The steel is widely used in aerospace engineering and medical instruments, etc. due to its high strength, corrosion resistance and weldability [5,7]. However, heat treatments, used in practical engineerings, play an important role in determining the internal microstructure which governs mechanical responses of FV520B. Therefore, it is necessary to investigate the correlation between heat treatments and mechanical behavior useful for directing the mechanical design.

In the present paper, the infrared thermographic method was employed to explore influence of different heat treatments on FV520B steel. Fatigue limits of two type steels were determined by the intrinsic dissipation. The internal microstructural changes were studied to understand the fatigue process.

2. Theoretical models of fatigue damage indicators

Relative temperature increment. Fatigue damage is known as energy dissipation accompanied by temperature changing. The temperature linked with energy dissipation enables us to understand the energy transformation, toughness reduction and damping vibration of materials. Therefore, the fatigue process can be qualitatively evaluated using the relative temperature increment.

During fatigue tests, to avoid any possible errors induced by the environmental perturbation and the experimental system sensitivity, the relative temperature increment ΔT on the hot-spot zone of the specimen surface is used to describe fatigue damage status:

$$\Delta T = T_m - T_0 \tag{1}$$

where T_m is the average temperature on the zone; and T_0 is the initial temperature.

Standard deviation of stress. Microcracks often initiate from local points due to the stress concentration. The fatigue damage distribution is not uniform when a material suffers from cyclic loading. The distribution of the local stress can be described by the standard deviation. The stress state on the hot-spot zone, due to the local high stress, enables us to qualitatively identify the critical location responsible for the final fracture. Accordingly, the economic losses caused by the sudden fatigue fracture might be greatly decreased by analyzing this damage indicator.

The stress level used here is the thermoelastic stress calculated by the equation below:

$$\Delta T = -\frac{\alpha}{\rho C_p} \cdot T \cdot \Delta\sigma \tag{2}$$

where α is the coefficient of linear expansion; C_p is the specific heat capacity; ρ is the material density; T is the absolute temperature; $\Delta\sigma$ is the change in the sum of principal stresses; and ΔT is the change in temperature.

The stress pattern can be visibly obtained using the infrared camera, and each pixel stands for a point in the selected zone Ω. Thus, the standard deviation of the stress can be written as:

$$\sigma_{\mathrm{SDS}} = \sqrt{\frac{1}{N}\sum_{x,y\in\Omega}(\sigma(x,y)-\sigma_{\mathrm{m}})^2} \tag{3}$$

Where σ_m denotes the average stress in the zone Ω; $\sigma(x, y)$ denotes the stress value at the point (x, y); and N denotes all the points in the zone Ω.

Intrinsic dissipation. Based on the small perturbation hypotheses, fatigue test is considered as a quasi-static dissipation process. The local coupled thermomechanical equation is derived [8]:

$$\rho \mathrm{C}_{\mathrm{p}} \dot{\mathrm{T}} - k\nabla^2 T = (\sigma - \rho\frac{\partial\psi}{\partial\varepsilon}):\dot{\varepsilon} - \rho\frac{\partial\psi}{\partial\alpha}\cdot\dot{\alpha} + \rho T\frac{\partial^2\psi}{\partial T\partial\varepsilon}:\dot{\varepsilon} + \rho T\frac{\partial^2\psi}{\partial T\partial\alpha}:\dot{\alpha} + \gamma^e \tag{4}$$

where k is the heat conduction coefficient; σ denotes the stress tensor; ψ is Helmholtz free energy; ε is the strain tensor; α is internal variables; and γ^e is the external heat resource.

The intrinsic dissipation is defined as:

$$d = (\sigma - \rho\frac{\partial\psi}{\partial\varepsilon}):\dot{\varepsilon} - \rho\frac{\partial\psi}{\partial\alpha}\cdot\dot{\alpha} \tag{5}$$

In fact, the intrinsic dissipation describes the dissipated energy due to inelastic effects, and it is an important part of the non-linear energy dissipation for materials and components subjected to fatigue loading. The infrared thermographic method can be used to quantitatively evaluate fatigue damage status, and accordingly the fatigue limit can be fast determined.

3. Experiment investigations

Material and specimen. The studied material is FV520B [7]. Its mechanical properties are greatly affected by heat treatments. Thus, two type specimens (Figure 1. Size of the specimen) were machined from two plates. One plate was just annealed (type A), and the other was treated with treatments in Ref.[9] (type B).

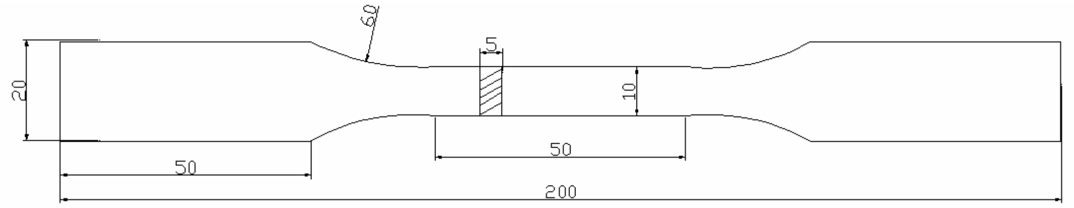

Figure 1. Size of the specimen (unit: mm)

Experimental procedures. Fatigue tests were carried out at room temperature without disturbance of the external heat resource. The testing system is composed of MTS810 system, infrared camera, lock-in module, computers and corresponding softwares [9].

Before tests, all the specimens were polished with fine grit papers, and then painted the specimens black to improve the heat radiation. The stress ratio is set as R=-1 with a frequency of 20Hz. The stepwise loading procedure was applied to the same specimen. To avoid fatigue damage accumulation, the stress was applied from 100MPa with steps of 50MPa until fracture. The thermal images on the hot-spot zone were recorded by the infrared camera to perform the subsequent data analysis.

3. Results and discussion

Qualitative identification of the fatigue damage. Temperature evolution is mainly attributed to the thermoelastic effect, plastic effect and heat conduction. The fluctuating temperature is due to the thermoelastic effect. The temperature amplitudes increase with the increasing cyclic loading. However, the thermoelastic effect has no contribution to the average temperature [8]. Figure.2 exhibits the relative temperature evolution of the two type specimens, showing the almost same trend.

The elastic stress controls mechanical responses of tested specimens when the stress is less than 300MPa. At this term, the specimen mainly takes place elastic deformation, and the temperature increment are mainly induced by non-plastic effects, i.e. viscosity effect etc. If the stress is higher than the fatigue limit, microcracks will initiate from the specimen boundaries, such as: the corner and the free surface. They initiate along the axial direction of 45^{o}, and then coalesce to form a main crack. The main crack propagates perpendicular to the principal stress direction. The plastic strain energy accumulates with the fatigue evolution. Most of the mechanical energy is dissipated as heat energy heating up the specimen. There are，however, still some different between the two type steels. The temperature increment of the type B is generally less than that of the type A. That is attributed to the slow evolution of internal microstructures of the type B, indicating its better fatigue resistance.

As a consequence, heat treatments [9,10] improve the microstructure of the type B (such as dislocation distribution and defect density, etc.), and accordingly enhance its mechanical properties.

Figure.3 presents variations of the stress standard deviation of the two type steels. There is no obvious plastic deformation when the applied stress is lower. Accordingly the standard deviation is relatively small. If the stress is higher than the fatigue limit, it sets to increase sharply in the local zone due to stress concentration. The break point indicates that the mechanisms related to fatigue failure have changed into plastic effect. Local stress concentration, due to pores and impurities, governs the stress distribution. The damage status can be qualitatively identified by the standard deviation to avoid the sudden fracture. From Figure.3, the standard deviation of the type B is small relative to the type A since the grain refinement due to heat treatments improves the arrangement of the internal microstructure, which makes the type B take on better fatigue resistance.

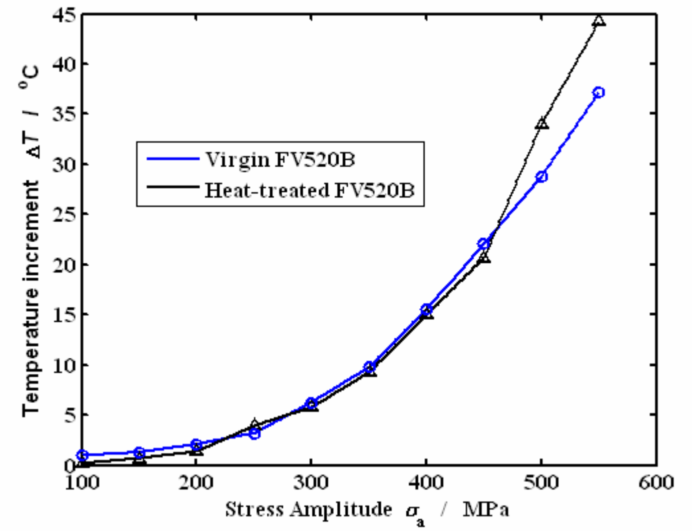

Figure.2 Relative temperature increment

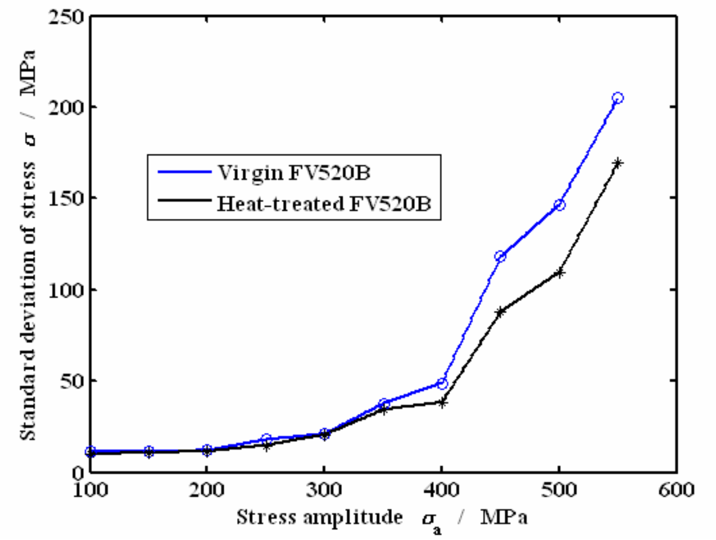

Figure.3 Standard deviation of stress

Fatigue limit evaluation. From Figure.2 and 3, the fatigue limit of the type B should be higher than that of the type A. In this part, the intrinsic dissipation shown in Figure.4 was utilised to get their fatigue limits. The break points are in the range of 250MPa~350MPa. The intersection of the two straight lines denotes the corresponding fatigue limit [11]. Thus the fatigue limit of the type A is

291MPa, and 319MPa for the type B. Fortunately, using the traditional method, the fatigue limits of the type A and B are 274MPa and 310MPa, respectively. The low values of errors, 6.2% and 2.9%, confirm the reliability of the infrared thermographic method in predicting fatigue parameters of materials with different heat treatments. To verify that the fatigue limit of the type B is higher, two fatigue tests, with the same cyclic stress 400MPa, were carried out to compare their fatigue life. The life of the type A is 141606 cycles, and 300748 cycles for the type B, confirming our results.

It is different for the variation of energy accumulation and heat dissipation during different fatigue process. The above fatigue tests can be divided into three phases. At lower stress, i.e. 100MPa~300Mpa, the temperature increases slowly, and the intrinsic dissipation is practically null. The internal microstrucutre evolution is reversible under the elastic stress. However, when the stress is close to the fatigue limit, the local stress may be beyond the yield limit due to the stress concentration in micro-scale. Consequently, the slip band begins to form, and numerous microcracks initiate here. Fatigue damage sets to accumulate continuously. If the stress is higher than 450MPa, all the three damage indicators, related to the final failure, increase drastically.

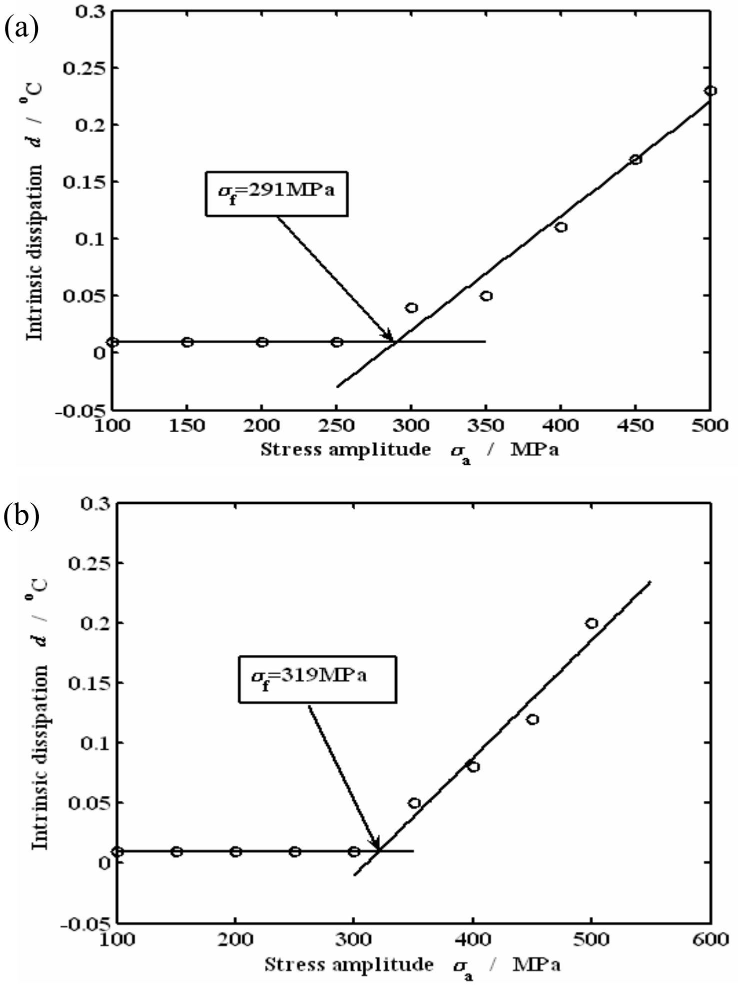

Figure. 4 Fatigue limit by the infrared thermographic method: (a) the type A; (b) the type B

4. Conclusions

[1] The infrared thermographic method enables us to qualitatively and quantitatively evaluate fatigue behavior of materials with different heat treatments.

[2] All the three fatigue damage indicators can describe the fatigue damage process. The macro-phenomenon and internal microstructure evolution are associated by the energy theory.

[3] The low errors of the predicted fatigue limits demonstrate the reliability of the infrared thermographic method in predicting fatigue parameters of materials and components.

[4] It is a fast and accurate technique for fatigue evaluation using various damage indicators resorting to the infrared technique. Consequently, the method may be used to identify the fatigue damage status of structures in service in the future.

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