NONDESTRUCTIVE EVALUATION OF FATIGUE IN TITANIUM ALLOYS

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ABSTRACT

Dissipated heat has been measured by thermographic technique during fatigue experiments on Ti-6Al-4V. Surface temperature of the specimen was found sensitive to the amount of fatigue damage accumulated in the material. An increased heat dissipation due to fatigue can be related to continuous change in the microstructure (increased dislocation density, stacking faults etc.) of the material. A method based on passive thermography can be proposed to monitor damage accumulation in Ti-6Al-4V due to cyclic loading.

INTRODUCTION

Cyclic loading of materials continuously degrades the microstructure and eventually leads to catastrophic failure. The methodologies used for predicting the fatigue and fracture life of materials assumes a pre-existence of a crack and examines the behavior of its growth under cyclic loading. These approaches have provided excellent design criteria for materials as well as components [1]. Although presence of a crack and its growth is detrimental for the life of the material, the processes that lead to the formation of cracks is very important in understanding the degradation of material and to develop experimental techniques to detect the onset of degradation and failure. At present, no reliable technique is available, neither to predict nor to detect the onset of failure in materials. Recently a nondestructive method based on nonlinear acoustics has been used to follow continuously fatigue damage accumulation in titanium alloys [2]. It has also been observed that heat generation caused by internal friction during fatigue loading in steel samples can be utilized to study damage accumulation [3,4]. The aim of the present research is to investigate the applicability of infrared (IR) thermographic method of measuring heat generation during cyclic loading of titanium alloys to continuously monitor the progression of fatigue damage.

In order to detect heat generated in a material by passive IR thermography, an effective method is required to excite heat in the specimen. In the present work mechanical loading has been applied to generate heat. It is also possible to use ultrasonic waves to load the sample to induce heat [5,6].

Under a load, the temperature of the material changes, and the characteristics of the changes in temperature is detected with IR-thermography. The change in temperature is caused by two separate mechanisms. One of the mechanisms is thermoelasticity of the material, while the other, which is more important for fatigue characterization, is the heat dissipation caused by internal friction [7]. An analysis of the dissipated heat as the material is fatigued is used for the investigation of damage accumulation. IR thermography has local resolution and takes a short time (order of a few seconds) to acquire the data in a non-contact way. Hence, it has potential to be used in field applications.

For a reliable use of thermal quantities for fatigue characterization, a fundamental understanding of the mechanisms governing heat dissipation is required. These temperature effects have to be related to the changes in microstructure due to fatigue damage [8,10].

EXPERIMENT

Material

The material chosen for the experiments is an alloy of titanium, Ti-6Al-4V. It has a duplex microstructure, equi-axed grains with grain sizes of approximately 25-50 μm. Cylindrical dog-bone samples (ASTM-standard, diameter 6.35 mm) were machined out of large plates for the experimental measurements.

Passive thermography

The specimens were subjected to sinusoidal cyclic loading in a fatigue machine (Figure 1). An infrared camera, operating in a long wavelength system (8-12 μm; Hg-Cd-Te detector), with temperature resolution $\Delta T \approx 0.2$ K and frame rate 25 Hz, was placed in front of the fatigue machine at a distance of 1 m. In order to increase the emissivity, a polymer coating was sprayed on to the specimen surface. Custom developed software allowed the performance of automatic, time dependent measurements and storage of frame sequences. Further, the software enabled averaging of frame sequences in order to increase accuracy and to determine the dissipated heat.

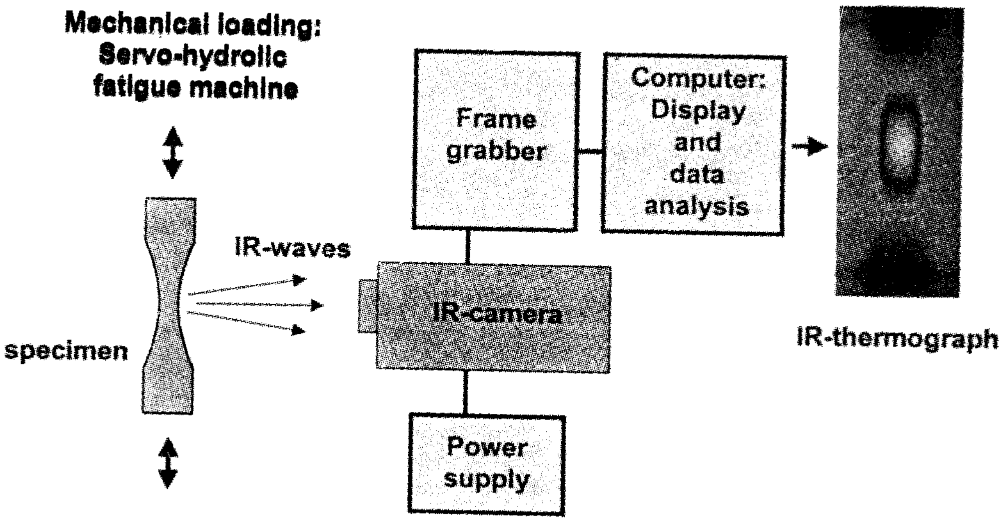

Figure 1: Experimental set-up used for passive thermography

Evaluation of dissipated heat

During the cyclic loading process, a variation of temperature ΔT can be measured on the specimen surface. The temperature ΔT in the adiabatic regime of negligible heat conduction, is the superposition of temperature variations due to thermo-elastic effect ΔT_{el} and dissipated heat ΔT_{diss}.

Thermoelasticity is a reversible thermodynamic effect caused by a change of the internal energy due to mechanical elastic strain. In metals (positive elongation coefficient), an increase of temperature due to compressive stresses and a decrease due to tensile stresses is observed [7].

The reason for an irreversible temperature enhancement is the dissipated energy, which is a result of microstructural processes during fatigue loading.

The temperature variation ΔT measured during the experiment is defined as the difference between the temperature at the center of the specimen and an unloaded reference specimen temperature. The use of a reference specimen eliminates uncertainties introduced by room temperature fluctuations. The changes in the temperature due to thermoelasticity of the material follow the period of the mechanical loading (Figure 2). Sequences of 10-100 video frames were stored and averaged to calculate the average temperature enhancement due to heat dissipation and to eliminate the thermoelastic effect.

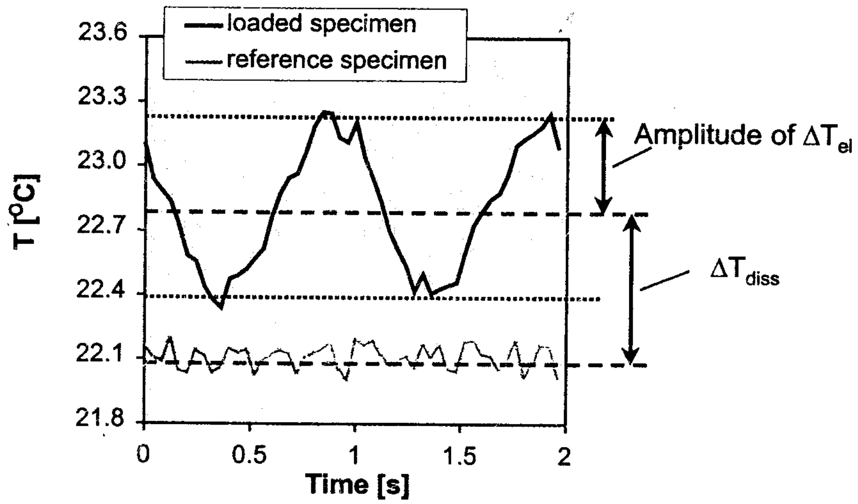

Figure 2: Time dependent oscillation of temperature due to thermo elasticity and evaluation of ΔT_{diss}

RESULTS AND DISCUSSION

Influence of loading parameters on heat dissipation

The influence of mechanical loading parameters (frequency, stress amplitude σ_a, mean stress σ_m) on the dissipated heat was investigated in fatigue experiments. These experiments provided an estimation of the most effective loading parameters for excitation of dissipated heat and its lifetime dependence.

In each experiment, a gradual increase of dissipated temperature ΔT_{diss} was observed from the beginning of the cyclic loading until fracture. A typical ΔT_{diss} (N) curve is presented in figure 3. The arrow indicates the final fracture at N_f=85,852 cycles. The IR-thermographs in figure 3 show the distribution of temperature due to heat dissipation at 3%, 63% and 98% of the specimens lifetime.

Several specimens were subjected to four different loading frequencies of 1, 3, 10, 30 Hz, at constant stress condition (σ_m=467.5 MPa, σ_a=382.5 MPa). If the loading frequency is increased from 1 to 10 Hz, ΔT_{diss} close to the fracture grows up from approximately 0.3 to 1.6 ^{o}C and the fatigue life, N_f, changes from approximately 30,000 to 150,000 cycles. An increase in the temperature can be explained based on the higher rate of dissipated energy during a constant time interval. However, the significant increase of lifetime within this frequency range is surprising. A possible reason may be a shift in the dynamic yield strength due to a higher loading frequency [9]. At 30 Hz, no further increase of both these quantities was observed.

At a loading frequency of 30 Hz, the influence of mean stress σ_m and stress amplitude σ_a, was examined. For the R-ratio $R = (\sigma_m-\sigma_a)/(\sigma_m+\sigma_a)$ from 0.06 to 0.17 (tensile stress range) increased mean stress and stress amplitude contributed to a dramatic increase of ΔT_{diss} and to a reduced fatigue life N_f. Simultaneously the slope of the curves changed from nearly linear to exponential (figure 4). Mean stresses σ_m enhancement from 430 to 540 MPa (σ_a=382.5 MPa) resulted in an drastic increase of ΔT_{diss} from 0.49 ^{0}C to 54.5 ^{0}C close to the fracture. Fatigue life was reduced from 220,686 to 15,078 cycles. For stress amplitudes σ_a = 382.5 to 415 MPa (σ_m=467.5 MPa) ΔT_{diss} close to fracture varied from 1.45 to 52.5 ^{0}C and reduced the fatigue life N_f from 150,527 to 34,882 cycles.

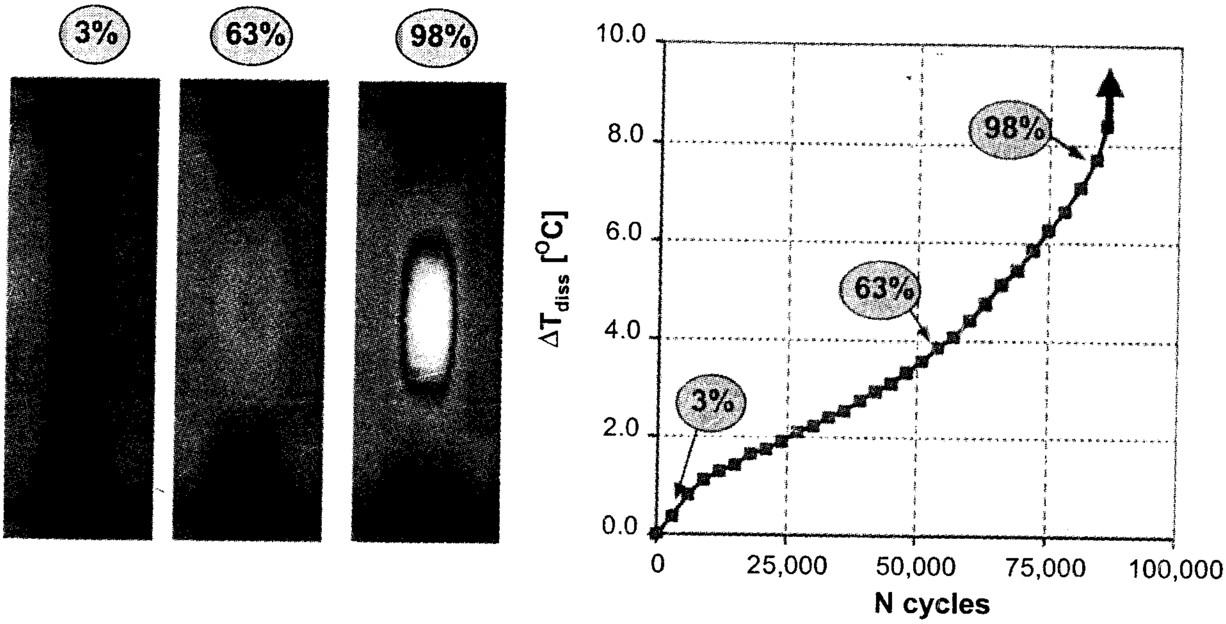

Figure 3: ΔT_{diss} (N) curve evaluated in a fatigue experiment (σ_m=467.5 MPa, σ_a=400 MPa, 30 Hz); IR-thermographs measured at 3%, 63%, 98 % of the fatigue life N_f=85,852 cycles

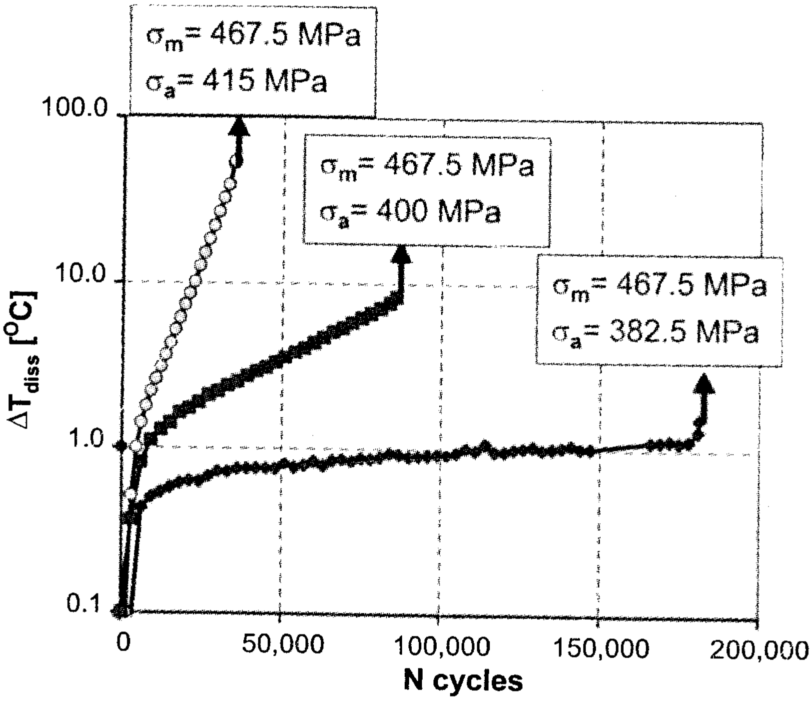

Figure 4: ΔT_{diss} (N) curve evaluated in fatigue experiments at low R-ratios for amplitudes σ_a: 382.5 MPa, 400 MPa, 415 MPa (30 Hz, σ_m=467.5 MPa)

Additionally a few specimens were subjected to a loading at R= -1 (σ_m=0 MPa, σ_a=600 MPa) in order to investigate the influence of compressive stresses. In contrast to the previous discussed results (R≈0.1) a decrease of ΔT_{diss} was found after 7,000 cycles (figure 5).

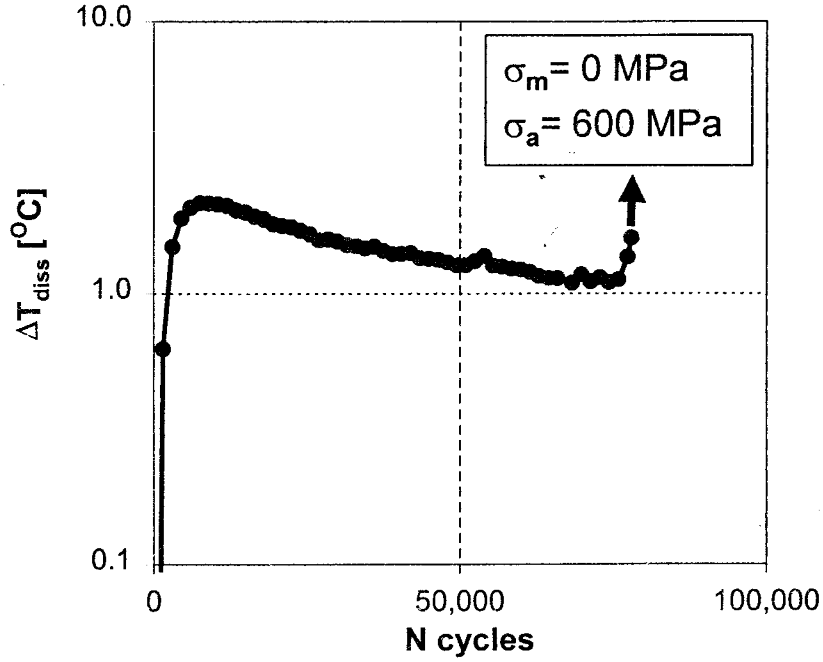

Figure 5: ΔT_{diss} (N) curve evaluated in a fatigue experiment at R= -1 (σ_m=0 MPa, σ_a=600 MPa, 30 Hz)

Figure 6 summarizes the results of experiments performed at 30 Hz and low R-ratio (R=0.06-1.7). High amounts of dissipated heat ΔT_{diss} are related to short lifetimes. Both ΔT_{diss} at 99% and 33% of the fatigue life show a correlation to the total number of cycles until fracture. Thus, a prediction of lifetime may be possible already within the early stages of the fatigue process. This result indicates the applicability of thermal methods for prediction of the fatigue life.

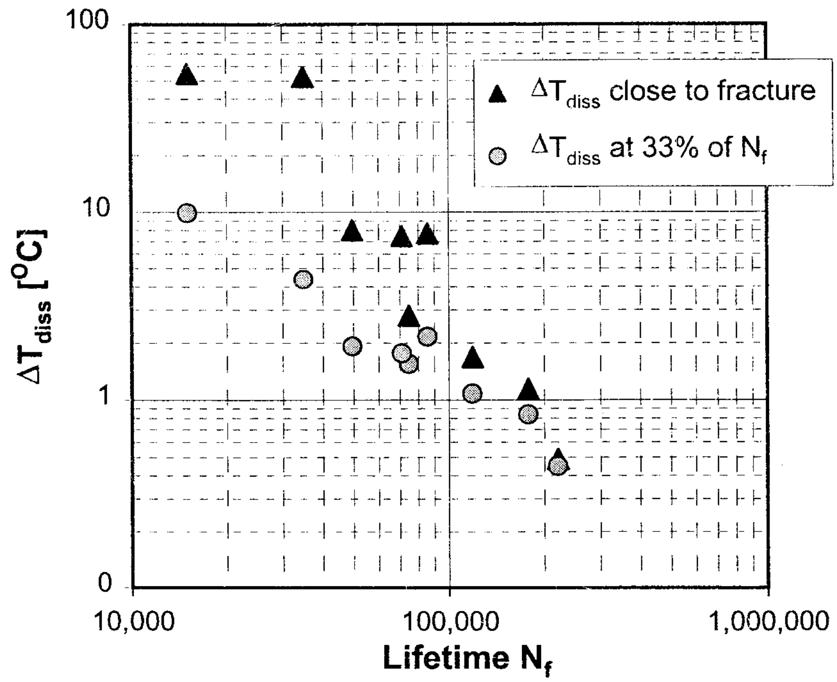

Figure 6: Relation of ΔT_{diss} to fatigue life N_f evaluated at 30 Hz and R=0.06-0.17

CONCLUSIONS

Temperature enhancement due to dissipated heat has been measured with IR-thermography. In a series of fatigue experiments on Ti-6Al-4V, a correlation of the fatigue life to ΔT_{diss} was observed. In addition, the shape of ΔT_{diss} (N) curves varies characteristically with the lifetime. The specimen's temperature due to heat dissipation already indicates the lifetime at 33% of the fatigue loading. This might be a powerful instrument to study fatigue processes and to monitor the fatigue damage accumulation. Further advantages of this method are high speed, non-contact and the capability of local resolution.

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