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On-line detection of fretting fatigue crack initiation by lock-in thermography

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ABSTRACT

Lack of accurate methodologies to detect micro-cracks in fretting fatigue experiments is a barrier to better understand the physics of the crack initiation phenomenon. In this study, the feasibility of thermography for on-line detection of micro-cracks in a closed contact during fretting fatigue experiments is investigated. Temperature variations in four regions of interest at the specimen surface are recorded and processed on-line based on a lock-in methodology to extract the first harmonic temperature amplitude. Following running-in and stabilization stages, the initiation of cracks leads to a rise of the stabilized first harmonic temperature amplitude for the specific region of interest where cracks are located. After that, tests are stopped and samples are inspected for cracks by optical microscopy.

1. Introduction

Fretting is a small amplitude reciprocating movement which may occur between contacting surfaces subjected to cyclic loads or vibrations. Under fretting conditions, two sliding regimes (partial slip and gross slip) can be observed. Usually cracking is the dominant mechanism for failure in partial slip, but wear is often observed for gross slip. If the partial slip regime takes place in combination with fatigue, lifetime can be significantly reduced [1].

Fretting fatigue lifetime is composed of both crack initiation and crack propagation. Being able to separate these two parts would allow to define correct remedies to improve total lifetime of materials or components since different techniques are utilized to increase the duration of crack initiation and of crack propagation. To predict the initiation time for fretting fatigue, multi-axial fatigue models and short crack arrest methodologies have been adopted and validated off-line by conventional optical microscopy [2–7]. Such approach requires to stop the tests and destructively inspect the samples. If on the other hand a test would be stopped, the specimens non-destructively inspected and the test restarted, it is impossible to maintain identical contact conditions. On-line techniques not only allow to avoid this issue but may also reveal how cracks are formed if a very early stage of crack initiation can be detected. However, there is very limited scientific proof of such on-line techniques. To our best knowledge, potential drop techniques were utilized to measure crack initiation during fretting fatigue tests [8,9], acoustic emission was used to investigate fretting wear [10] and quantify crack propagation modes in fretting fatigue [11].

Two thermography based approaches are commonly applied to investigate cyclic loadings. One is the analysis of temperature variations due to thermo-elasticity or thermal stress analysis (TSA) and the other is the analysis of mean temperature evolution to quantify plastic dissipation [12]. Based on the latter approach, some researchers measure mean temperature evolution only at the beginning of the experiment to detect the onset of microplasticity which allows to predict the fatigue limit of materials [13–15]. Mean temperature evolution can also be monitored until specimen failure and the number of cycles to crack initiation is determined based on crack-induced plasticity [16,17]. Combined effects of thermo-elasticity and energy dissipation methods have been used to determine the damage threshold in case of plain fretting [18]. Thermal images are recorded during the early stage of the plain fretting tests and a post-processing technique, based on a least squares curve fitting, allows to detect the onset of microplasticity. Because of the mentioned feasibility of thermography for microplasticity detection in both plain fretting and plain fatigue, the thermo-elasticity approach and a lock-in algorithm for on-line processing is adopted as on-line methodology to determine the number of cycles to crack initiation during fretting fatigue tests.

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Table 1
Mechanical properties of AL2024-T3 and S235JRC.

Materials		σ_y [MPa]	σ_{utl} [MPa]
AL2024-T3	Specifications	> 325	> 450
	Measured	383	506
S235JRC	Specifications	> 355	> 470
	Measured	650	700

2. Experiments

2.1. Experimental set-up

Fretting fatigue tests using cylindrical pads against a flat specimen have been performed and monitored with an infrared camera under ambient conditions. Materials of the pads and the specimen are identical and made of aluminum alloy AL2024-T3 and structural steel S235JRC (see Table 1 for mechanical properties). The test set-up is shown in Fig. 1 [19]. Conditions of fretting fatigue tests were selected to realize a partial slip regime and to ensure that no global plasticity would occur in the test specimens (see Table 2 and Fig. 2). Both the specimen and pads were painted in black to improve their thermal emissivity. Their dimensions are the same as in [20] except that the thickness of the S235JRC specimen and pads are increased to 5 mm and the pads radius of S235JRC is 150 mm (see Fig. 1). The infrared camera model is InfraTec series 8300 with a telephoto lens of 50 mm focal distance. Its sensitivity at 25 °C is about 25 mK. The camera is installed at a distance of around 200 mm and perpendicular to the specimen surface. This corresponds to a pixel size of the thermal images equal to 65 µm, the minimum pixel size achievable. The tests are run with fatigue ratio ($\sigma_{min}/\sigma_{max}$) of 0.001, tangential load ratio (Q_{min}/Q_{max}) of −1, a constant normal load, P, and loading frequency of 5 Hz. The frame rate applied in this study is taken to be 50 Hz. For a loading frequency of 5 Hz, 10 data points are recorded for each load cycle, which is considered to be oversampling (larger than the Nyquist frequency of 5/2 Hz) and allows better accuracy of data processing [21].

2.2. On-line data acquisition

Usually thermal images are captured before the data is extracted and post-processed which leads to storage issues due to the size of thermal images. This common practice does not allow continuous measurement during the entire experiment. In this work, thermal images are recorded only for the first 1000 cycles during which a steady state partial slip regime is reached. Locations of the highest temperature at the contacts, R_1 and R_2, can be defined as visualized in Fig. 3. These regions are anticipated to be the regions with the highest stress concentration and thus crack initiation. On the other hand, regions R_3 and R_4 are selected above and below the contact regions, respectively. These are chosen for reference purposes, and their temperature difference allows to monitor the tangential force based on basic thermo-elastic calibration between the temperature variation and the stress range. Dimensions of all regions of interest are 10 by 20 pixels, which is around ax2a as selected in [18] where a is a contact half-width (63 µm for AL2024-T3). The smaller the region of the interest, the smaller detection threshold can be. But it risks that the location of the region of interests are misplaced to the real location of the crack because the location of the contact area is estimated with larger uncertainty with the available pixel size. After the first 1000 cycles, the coordinates of all regions of interest are inserted into a Matlab script and from then on average temperature data are recorded on-line. The data acquisition is continuous during the entire duration of the fretting fatigue tests. The accuracy of this on-line data acquisition has been verified with the off-line data extraction for all regions of interest. As an illustration the comparison for region R_1 is shown in Fig. 4. An excellent data matching can be observed.

2.3. Temperature modulation during fretting fatigue tests and concept for crack initiation

Heat sources in fretting fatigue experiments are fretting friction,

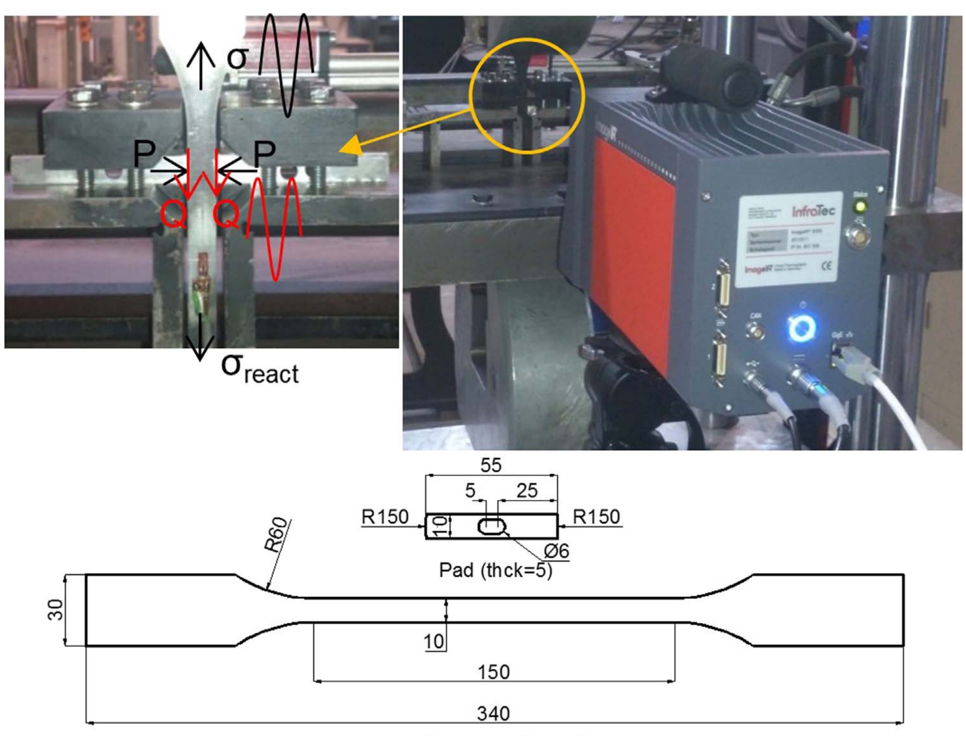

Fig. 1. Experimental set-up.