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# Nondestructive sizing and localization of internal microcracks in fatigue samples

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**Abstract**

A large number of fatigue experiments on standardized samples is required for the development of databases of the fatigue properties of specific material systems. To facilitate such studies, different visual monitoring methods for surface fatigue cracks have been used; however, the problem of monitoring internal fatigue crack initiating during cold dwell fatigue of Ti is much more complicated. This paper describes the development and integration of several nondestructive evaluation methods for monitoring and sizing microcracks in titanium fatigue samples. For in situ monitoring of crack initiation and evolution ultrasonic Lamb wave signals are excited and acquired in the sample continuously during fatigue tests at different levels of fatigue load using a high-speed data acquisition system. Localization of the secondary cracks is done by both the in situ ultrasonic method and an ultrasonic immersion scanning method here referred to as "vertical C-scan" (VC-scan). The VC-scan is developed for imaging small cracks aligned normal to the fatigue sample axis. Microradiography has been performed on fatigue samples to confirm the localization and sizing of the detected cracks with other ultrasonic NDE techniques. The fusion of data from different NDE techniques provides useful information on the initiation, location, shape, size and growth history of fatigue cracks.

*Keywords:* In situ ultrasonic monitoring; Microradiography; Dwell fatigue; Crack initiation

## 1. Introduction

Due to their high specific strength, high service temperature and good fracture toughness, titanium alloys are widely employed in aircraft engine components, e.g. compressor blades and spools. The strength of these alloys is manipulated and maximized by controlling their microstructure during thermomechanical processing. However, it has been reported that these alloys show anomalously high primary creep strains at low temperatures ($0.2T_m$ (K)) and low applied stresses ($0.69\sigma_Y$) [1]. The accumulation of high creep strain results in significant reduction of fatigue life during dwell cycle fatigue testing. Alloys that contain coarse $\alpha/\beta$ microstructures have been found to be most susceptible to dwell cycle fatigue [2]. The mechanism of initiation of cold dwell fatigue crack in Ti-6242 alloy has been investigated [1–3], but the details of the interaction between microstructure, loading history and fatigue life are not fully understood. To advance understanding, experimental data on fatigue crack initiation and evolution are needed, which must be obtained from a large number of fatigue experiments. The fatigue crack initiation site and the failure mode may be, in principle, inferred from a sample fractograph; however, this is not always possible and the time of crack initiation cannot be so determined. A straightforward approach to understanding the crack initiation mechanism may be direct observation of the microstructure surrounding a just-initiated dwell fatigue crack. For this purpose, early detection and accurate localization of the initiated small cracks by in situ sample monitoring during fatigue experiments are of great importance.

Commonly, fatigue cracks are initiated from surface defects. One difference in dwell fatigue crack initiation in Ti alloys is that such cracks are usually initiated in the bulk

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of the material (even for non-shot-peened samples). In general, monitoring of subsurface fatigue crack initiation is a difficult task. Furthermore, in Ti-6242 alloy, the dwell fatigue cracks initiate at multiple sites, which adds complexity to the crack monitoring. In addition, the shape and size of the fatigue sample allows limited room for access to the cracks.

In this paper, different nondestructive evaluation methods developed in this work to obtain information on initiation, propagation and location of dwell fatigue cracks in Ti-6242 alloy samples are presented. An in situ ultrasonic guided wave technique developed for monitoring of fatigue crack initiation in Al-2024 alloy [4,5] is implemented during dwell/cyclic fatigue and creep tests of Ti-6242 alloy samples. The difference with previous work [4,5] is that in that work a surface corrosion pit was used as a stress raiser and thus the crack initiation site was known and the crack initiation was monitored as the change of the ultrasonic signal reflected from the pit. In the current experiments with Ti-6242 samples, the crack initiation notches are not introduced and the signals reflected from initiated microcracks are masked by ultrasonic noise induced by microstructural scattering (how this issue can be overcome is discussed in the paper). For localization of secondary cracks, an ultrasonic scanning method (vertical C-scan (YC-scan)) is developed. This technique is applied after fatigue testing in conjunction with microradiography for the precise localization and sizing of the cracks. Data on crack localization by ultrasonic methods validated by microradiography and imaging results are compared and discussed.

## 2. Samples and fatigue tests

Cylindrical and rectangular flat standard fatigue samples (ASMT E606-92) were used in the experiments. The cylindrical samples were 5 mm diameter and 19 mm length in the gage section. One of the cylindrical samples was shot peened. The rectangular samples were prepared from high microstructure Ti-6242 $\alpha/\beta$ forge and machined to flat fatigue specimens with 2 mm thickness, 6 mm width and 12.5 mm length in the gage section. To study the crack initiation mechanism, the samples had no crack initiating notch; thus, crack initiation can be associated with specific features of the microstructure (this microstructural study has been performed by others and is not reported in this work). The samples were tested to failure in dwell fatigue, regular low cycle fatigue and creep modes.

## 3. Microradiographic characterization of fatigue cracks

The ultrasonic methods reported in the following sections were validated and supported by microradiographic imaging using a 5 μm focal size, 225 kV FeinFocus® X-ray source. The X-ray source, an object and the X-ray detector (film or image intensifier) are aligned linearly along the optical axis. A precision positioning system with three linear (with 2 μm resolution) and one rotating (with 0.01° resolution) computer-controlled axes is used to control the position of the sample. An additional high-resolution linear axis is used for translating the position of the image plane. A two-directional manipulator is used for positioning of the X-ray tube. An image intensifier integrated with a CCD camera is used for real-time microradiography and also for alignment of the sample before film microradiography.

A micron resolution movement of the sample provides accurate projection magnification of the image. The X-ray exposure parameters have been carefully selected such that during exposure the focal spot size remains in the micro-focus region of the tube to get the optimum resolution. In the film microradiography, after alignment of the sample and the image plane the film is mounted on a 4-mm-thick lead plate and placed in the front face of the image intensifier, which in this case serves as a mechanical support. The exposed and processed films are digitized by illuminating them in front of a TV camera. A PCVision® Frame Grabber (from Imaging Technology) is used for digitization of the films and transferring the image to a PC. The digital profiles of the images are saved in the computer and further processed to obtain the X-ray intensities. Agfa Structurix D7 high-speed films were used for evaluation. Images with projection magnification of 16× have been selected as providing sufficient magnification and field of view. Radiographs have been enlarged optically to increase the detectability of the cracks.

## 4. In situ ultrasonic monitoring of dwell fatigue crack initiation and propagation

### 4.1. Experimental setup and procedure

To monitor the initiation and propagation of the dwell fatigue cracks, we have employed ultrasonic guided waves excited in the fatigue sample with phase velocity 3.1 mm/μs, which is somewhat above the surface wave velocity of 2.8 mm/μs (more precisely, at these frequencies and sample thicknesses (10 MHz mm) a combination of $S_0$ and $A_0$ Lamb waves is excited as a single-wave train). The transducer assembly is clamped onto the sample undergoing the fatigue test so that the ultrasonic reflection signals are collected without interrupting the fatigue test as shown in Fig. 1. For wave excitation and recording, a broad band longitudinal wave transducer with center frequency of 5 MHz is used with a specially designed polystyrene wedge to generate the Lamb wave in the 2-mm-thick Ti-6242 alloy sample as shown in Fig. 1. A surface wave reflector has been designed and mounted on the sample (Fig. 1(b)) to have a reference signal throughout the fatigue test, which will help in interpretation and processing of the signals acquired.

In situ monitoring of crack initiation and growth is performed by recording of ultrasonic Lamb wave signals