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Investigation of thermal effects on fatigue crack closure using multiscale digital image correlation experiments

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ABSTRACT

Hastelloy X, a nickel-based superalloy, has been extensively used for high temperature applications. In this work, Hastelloy X notched samples were used to investigate fatigue crack growth and crack closure at elevated temperatures. Isothermal, thermal jump, and thermal overload experiments at varying temperatures (up to 650 °C), were performed. Macroscale (2 μm/pixel) digital image correlation was performed on images taken at various stages of crack growth and microscale (0.4 μm/pixel) digital image correlation was used on images obtained directly behind the crack tip to quantify the local effects of crack closure. Experiments focused on the effects of isothermal conditions and thermal overloads on measured crack closure levels. Each isothermal experiment showed steady state crack closure levels of 0.30 while thermal jumps and thermal overloads created significant decreases (or, in some cases, complete elimination) in closure levels immediately following the temperature change. Similar to the case of mechanical overloads, as crack growth was continued beyond the plastic zone enlargement created by the thermal spike, closure levels were reestablished near the original steady state values. Competing mechanisms, including crack tip blunting, crack bifurcation, change in temperature, yield stress, elastic modulus, and plastic zone size, thought to be responsible for the changes in closure levels following the thermal jumps and during the thermal overload, were investigated.

1. Introduction

Over the past 100 years, extensive research has taken place in order to create a damage tolerant design approach incorporating possible fatigue damage of a structural component. The stress intensity factor has been employed as a key variable in predicting fatigue life. Early research into this area performed by Paris and Erdogan [1] and McEvily and Boettner [2] related fatigue crack growth rate, da/dN, to the stress intensity factor range, ΔK, through the well-known Paris relationship.

As a fatigue crack grows in a ductile material, it leaves behind a plastic wake. This plastic wake produces compressive forces that shield the crack from external loading. As a result, the crack does not fully open until a specific opening load is reached. This phenomenon, which causes the crack to "unzip" when loaded, is known as crack closure. In 1970, Elber discovered a relationship between crack growth rates and crack closure [3,4]. The conventional Paris relationship was thus modified by Elber to incorporate only the portion of the loading range, or the effective stress intensity factor range, experienced by the opened crack [3,4] as,

$$\frac{da}{dN} = C(\Delta K_{eff})^m, \quad \Delta K_{eff} = K_{max} - K_{open}, \qquad (1)$$

where da/dN is the crack growth rate for the effective stress intensity factor range, ΔK_{eff}. Various types of crack closure have been identified, including plasticity-, oxide-, roughness-, viscous fluid-, and phase transformation-induced crack closure [5].

Elber showed that a compliance change accompanied opening of the crack and that, by using a displacement gauge 2 mm behind the crack tip to measure the relative opening of the crack, the load level corresponding to the compliance change could be measured. Sehitoglu [6] found that crack opening load levels are typically higher than crack closing load levels and reach saturated levels with increasing crack length. Davidson [7] confirmed earlier statements by Horng and Fine [8] and Veccio et al. [9] that closure levels are different in center-notch specimens than for single-edge notch specimens. Carroll et al. [10] used macroscale and microscale methods to study crack closure of Ti at room temperature.

In this work, full-field methods developed by Carroll et al. in Ti specimens were employed. These methods included two different macroscale techniques for measuring crack closure through

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full-field measurements of stress intensity factors using digital image correlation (DIC). One method compared the measured stress intensity factor to the theoretical stress intensity factor in the absence of crack closure. The second method determined the crack opening level by a slope change in the stress intensity factor vs. load curve. These techniques, along with the local displacement gauge techniques of Riddell et al. [11] and Sutton et al. [12] were used to provide multiscale measurements of fatigue crack opening and closure loads.

Engineering components are often subjected to mechanically and thermally varying environments. Mechanical overloads have been extensively studied [13–21] but less is known about the impact of thermal overloads on fatigue crack growth even though high temperatures significantly affect material properties [22]. Some work has been done with crack closure at high temperature isothermal conditions. Babu et al. [23] studied stainless steel 316(N) weld metal and identified that roughness-induced crack closure was present at 300 K, while oxide-induced crack closure was present at 823 K. Kokini [24] succeeded in using a displacement method as well as a modified crack closure integral method to calculate stress intensity factors using finite element analysis for a cracked strip undergoing a thermal shock. Similarly, Giannopoulos and Anifantis [25] used finite element analysis to study two-dimensional crack closure under variable heating.

The present investigation is concerned with the effects of elevated temperature and thermal history on fatigue crack closure including isothermal, thermal jump (where one steady state thermal condition is elevated to another during fatigue loading), and thermal overload (where a single cycle temperature spike occurs during fatigue loading) conditions. Digital image correlation techniques were employed to quantify the levels of crack closure a specimen experienced as a function of thermal history. Crack propagation rates following a thermal overload, as well as crack tip blunting, crack bifurcation, and plastic zone size were considered. Section 2 explores the experimental methods and procedures used to quantify deformation at high temperature. In Section 3.1, the crack closure results are shown for the isothermal experiments at two different measurement length scales (micro- and macro-scale). The results from the thermal jump and thermal overload experiments are finally discussed in Sections 3.2 and 3.3.

2. Experimental methods

2.1. Material and specimen preparation

The single edge notch tension specimens used in this investigation were 75 mm by 7.0 mm by 1.3 mm pieces cut from a plate of Hastelloy X using wire electrical discharge machining (EDM). Hastelloy X is a nickel-based superalloy with an average grain size of 50 μm, and profuse annealing twins throughout the material [26]. Temperature dependent material properties for Hastelloy X, as provided by Haynes International are plotted in Fig. 1. Evolution of uniaxial stress–strain curves of Hastelloy X at various temperatures can be seen in [27]. Varying batches of Hastelloy X have been found to exhibit slightly different stress–strain behavior as a function of temperature due to inherent differences in the material.

Along one edge of the rectangular sample, a 1 mm long notch was cut using a 0.15 mm EDM wire. The specimen was then polished using 320, 600, and 800 grit polishing paper, successively. A speckle pattern was applied to the polished surface for DIC. The speckle patterns were made of either high temperature paint or 1–5 μm silicon particles adhered using a compressed air application technique [28,29]. The high temperature painting method of applying a speckle pattern is similar to the procedure developed by Efstathiou et al. for studying intermartensitic transformations in single-crystal NiFeGa [30] and was used in the earliest experiments. The silicon particle speckle pattern was used for the majority of the experiments described here as this method more easily facilitates identification of the crack tip during testing.

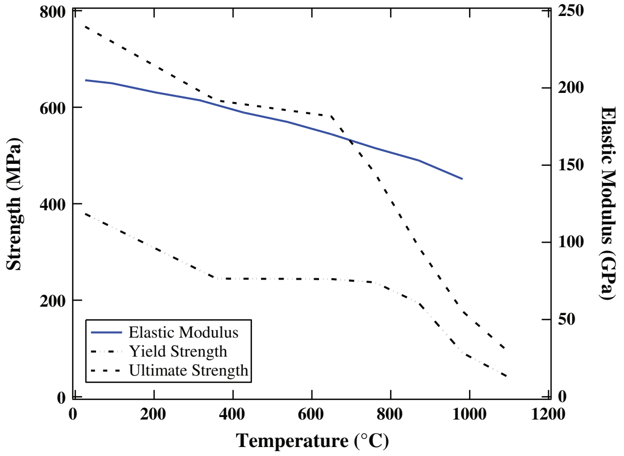

Fig. 1. Temperature dependence of elastic modulus and ultimate and yield strengths of Hastelloy X as provided by the manufacturer, Haynes International [31].

For these high temperature experiments, in addition to the speckle pattern deposited on the front surface of the sample, the back surface was painted with a high temperature, flat black paint to increase sample emissivity. This allowed the use of a Raytek infrared thermometer to monitor the specimen's temperature. In earlier efforts it was found that this infrared thermometer accurately captures the temperature of the specimen within ±10 °C.

2.2. Experimental procedure

In order to initiate and grow a crack from the notch tip, the specimen was fatigue loaded in axial tension at a frequency of 2 Hz using an Instron 8802 servohydraulic load frame in what will henceforth be referred to as "precracking." During the fatigue precracking, the theoretical mode I stress intensity factor, K_I, calculated for the single edge notch geometry used in this investigation, was maintained at 19 ± 2 MPa $\sqrt{\text{m}}$ by load shedding. K_I can be calculated by,

$$K_I = F\sigma\sqrt{\pi a} \tag{2}$$

where F is the dimensionless function given by Eq. (3), σ is the applied stress, and a is the total length of the crack (notch plus fatigue crack). In the expression for F, given by

$$F = 0.265(1-\alpha)^4 + \frac{0.857 + 0.265\alpha}{(1-\alpha)^{\frac{3}{2}}}, \tag{3}$$

and α is the crack length divided by the specimen width [32].

Images were taken during the precracking cycles at a rate of 8 images per cycle, using a Navitar 12× zoom lens with 2× adapter tube, and an IMI-1200FT digital camera with a 1600 × 1200 resolution, and then inspected in order to most accurately determine the crack length. Lighting was provided by fiber optic gooseneck lights as well as a fiber optic ring light. The load frame and the camera were synchronized by a LabView program. Fig. 2(a) shows the entire experimental set up used for all experiments in this work while Fig. 2(b) shows the red box from Figure (a) at a higher magnification. During loading, the load ratio R, the ratio of minimum load to maximum load, was maintained at 0.05 as to facilitate the presence of crack closure. With the crack grown to a total length (including the notch) of between 2.2 mm and 2.4 mm from