INVESTIGATION OF THERMAL EFFECTS ON FATIGUE CRACK CLOSURE USING MULTISCALE DIGITAL IMAGE CORRELATION EXPERIMENTS

BY

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THESIS

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ABSTRACT

This work investigates, at multiple length scales, the thermal effects on fatigue crack closure of Hastelloy X, a nickel-based superalloy. Using multiscale, digital image correlation (DIC), macroscale experiments were performed at 2x magnification (2 µm/pix), providing full-field crack closure measurements. Microscale experiments performed at 10x magnification (0.4 µm/pix), provided local crack closure measurements at varying locations from the crack tip, along the crack line. Using these techniques, fatigue crack growth experiments were performed on single-edge notch tension (SENT) specimens of Hastelloy X. A $\Delta K$ of 19 ±2 MPa$\sqrt{m}$ was maintained constant throughout the experiments along with an R ratio of 0.05.

Isothermal experiments were performed at room temperature (RT), 300 °C, and 550 °C. It was found through the microscale experiments that the level of measured crack closure increased as the crack tip was approached, as has been seen in the past. Local closure levels were the same between the room temperature and high temperature cases, to within a threshold of ±10% - the resolution of the microscale method. Through the macroscale experiments, it was shown that regardless of temperature, under isothermal conditions, the measured levels of crack closure were 30% ±10% of peak load.

Within the resolution of the measurement methods used here, under isothermal conditions, crack closure was shown to be independent of temperature. Variations in temperature however, caused a strong temperature dependent crack closure response. The thermal jump cases showed that a considerable thermal spike greatly affects the amount of measured crack closure following that increase in temperature. In the case of a 300 °C to 400 °C jump, no change occurred. However, in the cases where a more substantial thermal jump occurred, crack closure was either reduced (as in the 300 °C to 550 °C jump) or completely eliminated (as in the RT to 250 °C jump and the 300 °C to 650 °C jump). In the case of a thermal overload from 300 °C to 650 °C and then back to 300 °C, crack closure was seen to be extremely diminished following the overload, and to then gradually return to nominal levels once the fatigue crack had advanced outside of the enlarged plastic zone caused by the thermal spike.
Competing mechanisms including crack tip blunting, the change in temperature, the decrease in yield stress, the decrease in the elastic modulus, and the enlarged plastic zone ahead of the crack tip, are thought to be responsible for the changes in closure levels following the thermal jumps and during the thermal overload and were therefore investigated. In all cases where crack closure was eliminated following the thermal jump however, crack tip blunting was observed to be the dominant mechanism affecting closure. The blunted crack needed to reinitiate before further crack growth could occur.
To my father, for always answering my questions. To my mother, for patiently directing my questions to my father. And to my parents, for acknowledging that there are so many questions needing to be answered.
I would like to first express sincere thanks to Professor John Lambros for all of his support through this entire process. His suggestions, attention to detail, and experience have always been extremely helpful. Thank you as well to Professor Bob Dodds and Professor Huseyin Sehitoglu for your added guidance and knowledge that made this work possible. Thank you also to Dr. Ravi Chona at the AFRL who always greeted my research with a smile. Thank you to the Midwest Structural Sciences Center (MSSC) who funded my first two years of research and to NASA who awarded me the NASA Graduate Student Researchers Program (GSRP) fellowship that has continued my funding into this year. Thank you to Dr. Doug Wells, Dr. Preston McGill, and Dr. Phillip Allen at NASA who have already begun to ask great questions that have propelled my research forward.

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Lastly, I extend a million thanks to my family. To my dad who edited research proposals, my mom who taught me the value of a hot cup of tea, to my little brother, Lucas, who made sure that I took a break to come home every once in a while, and to my fiancé (soon to be husband) who always used my late nights working as an excuse to work late himself, supportively by my side; thank you from the depths of my heart. I would not be here without you all.
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1.1 Background and Motivation

Over the past 100 years, extensive research has taken place in order to eventually create an aggressive, damage tolerant design approach in response to the threat of fatigue damage to a structural component. The stress intensity factor, a parameter that describes the magnitude of the crack tip stress field, experienced by a cracked component during use at various temperatures is a key variable in predicting the fatigue life of the component. Early research into this area performed by Paris and Erdogan \[2\] and McEvily and Boettner \[3\] related fatigue crack growth rate, $da/dN$, to the stress intensity factor range, $\Delta K$, through the Paris relationship shown by

$$ \frac{da}{dN} = C(\Delta K)^m. \quad (1.1) $$

where $C$ and $m$ are material and loading dependent constants.

In 1970, Elber discovered the relations between crack growth rates and crack closure \[1\][4]. As a fatigue crack grows in a ductile material, it leaves behind a plastic wake, or a region of permanent plastic deformation on either side of the crack faces. A schematic, taken from [1], of the plastically deformed wake is shown by Figure 1.1. This plastic wake produces compressive forces which 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 instead of opening immediately upon loading, is known as crack closure. 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 \[1\][4],

$$ \frac{da}{dN} = C(\Delta K_{eff})^m, \quad \Delta K_{eff} = K_{max} - K_{open}, \quad (1.2) $$

where $da/dN$ is the crack growth rate for the effective stress intensity factor range, $\Delta K_{eff}$. This range is the difference between the maximum applied stress intensity factor, $K_{max}$,
and the opening load stress intensity factor, $K_{\text{open}}$. Elber showed that a compliance change accompanied opening of the crack and that, by using a displacement gage 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 found that crack opening load levels are typically higher than crack closing load levels and are independent of crack length [5]. Davidson confirmed earlier statements by Horng and Fine and Veccio et al. that the level of closure is different in center-notch specimens than for single-edge notch specimens [6][7][8].

Various types of crack closure have been identified, including plasticity-, oxide-, roughness-, viscous fluid-, and phase transformation-induced crack closure [9]. Many methods exist for measuring crack closure. Schijve described some methods that have been used with limited success including the eddy current method, the electrical potential drop method, and ultrasonic/acoustic methods [10]. A Digital Image Correlation (DIC) technique was first used for measuring closure by Riddell et al. and Sutton et al. by employing virtual displacement gages to measure the movement of subsets placed on either side of the crack flanks [11][12]. Using digital image correlation, Carroll et al. used two different macroscale techniques for measuring crack closure. One method measured stress intensity factors at a full-field level using the measured displacement field both behind and in front of the crack tip. The second method used the displacements near the crack tip to calculate the compliance offset. They used these together with the local displacement gauge techniques of Riddell et al. and Sutton et al. to provide multiscale measurements of fatigue crack opening and closure loads [11][12].
Modeling of the crack closure phenomena has also been extensive. Fleck determined the influence that specimen geometry and load level played on crack closure using a finite element analysis under plane strain conditions [13]. Using a finite element model, McClung and Sehitoglu showed that crack closure was strongly dependent on the displacements measured behind the crack tip as well as the total crack opening displacement [14]. Crack closure, despite being most often analyzed as a two-dimensional phenomenon (including in this investigation), remains very three-dimensional in nature. Riddell et al. performed crack experiments along with numerical simulations of crack growth. They found that the opening levels are fairly constant but increase near the surface of the specimen [11]. Roychowdhury and Dodds confirmed this when they provided an understanding for stress fields for a growing fatigue crack in mode I under small scale yielding. Specifically, they found that the laterally unzipping fatigue crack opens first at the centerplane of the specimen and then gradually opens towards the free surface [15].

Consequently, fatigue life of a structure or component can be dramatically affected by the presence or absence of crack closure. This is especially true in the context of high temperature, where yield properties can vary significantly. High temperature environments, such as the leading edge of a hypersonic airfoil or within the confines of an engine, experience extreme thermal conditions, especially in the context of thermomechanical fatigue where both loading and thermal conditions are cyclic. The components’ ability to survive these temperature and mechanical fluctuations is essential. The investigation of these elevated temperature conditions is therefore, of the utmost importance.

1.2 High Temperature Fatigue Crack Growth

High temperature fatigue crack growth research often focuses on fatigue crack propagation rates. Jablonski studied creep and oxidation of Hastelloy X at high temperatures [16]. Marchand et al. looked at comparisons between out-of-phase and in-phase crack growth rates for thermomechanical fatigue experiments in Hastelloy X [17]. They also showed that both transgranular fracture and intergranular fracture in the material experienced a unique relationship between crack growth rate and $\Delta K_{eff}$. Suzuki et al. showed that crack growth rates increase with increasing temperature in Hastelloy X [18]. Others have studied fatigue crack initiation at high temperature. Hong et al. compared low cycle fatigue data, at high temperature, of Hastelloy X to the Coffin-Manson relationship, or the relationship between the total strain range and the number of cycles to failure. They found that a change in slope in the Coffin-Manson plot occurred at 870 °C suggesting that fatigue crack initiation had
transitioned from transgranular to intergranular [19].

Some work has been done with crack closure at high temperatures. Babu et al. studied SS 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 [20]. Kokini succeeded in using a displacement method as well as a modified crack closure integral method to calculate stress intensity factors for a cracked strip undergoing a thermal shock using the finite element method [21]. Similarly, Giannopoulos and Anifantis used finite element analysis to study two-dimensional crack closure under variable heating [22].

Digital Image Correlation, which will be further explained in Section 2.3, studies have been undertaken at high temperatures. Lyons et al. were among the first to use DIC to obtain full-field deformation measurements at temperatures up to 650 °C. They validated that, when compared to experiments at room temperature, the DIC method was able to accurately measure mechanically and thermally induced strains at high temperatures [23]. Grant et al. used a similar experimental method to test this same hypothesis, though without the use of a physical speckle pattern applied to the specimen surface. This speckle pattern will be further explained in Chapter 2, Section 2.3 [24]. Pan et al. applied these same methods, this time with an applied speckle pattern to the surface, to measure deformation for a temperature range of room temperature to 1200 °C [25].

During fatigue cracking, the area in front of the crack tip is affected by residual stresses, crack tip blunting, as well as crack closure. These competing mechanisms help to determine the behavior of the fatigue crack. Following a tensile overload, the crack tip region experiences compressive residual stresses which most often cause a retardation of fatigue crack propagation accompanied by an increase in crack closure [26][27][28][29]. The region affected by the overload, and correspondingly the retarded crack propagation rates, is often seen to be proportional to the plastic zone size [30][31]. Crack tip blunting is also seen [30][32][28] and is viewed as a prominent mechanism in the retardation of the fatigue crack’s growth. Thermal overloads/underloads, as well as jumps in temperature could therefore, have a similar effect on crack closure levels.

1.3 Objectives and Outline of this Work

While the effects of tensile overloads have been well investigated, even with these high temperature experimental fatigue and DIC advances, the phenomena of thermal effects on crack closure remain largely unstudied. It is the goal of this work to investigate the role of increasing temperature on fatigue crack closure limits in a nickel-based superalloy. During
fatigue cracking, the area in front of the crack tip is affected by residual stresses, crack tip blunting, as well as crack closure. These competing mechanisms help to determine the behavior of the fatigue crack. Often driven by plasticity, it is logical that fatigue crack closure would be affected by both temperature conditions as well as thermal history. It is expected that sample-to-sample variability will arise resulting from crack face surface roughness, crack front curvature, and local microstructure, among others. To this purpose, the specific objectives of the work are as follows:

- Use multiscale digital image correlation techniques to measure crack closure levels at elevated temperatures.
- Study the effect that isothermal, elevated temperature conditions have on fatigue crack closure levels, as well as how thermal jumps and thermal overloads alter the measured crack closure levels.
- Determine the differences or similarities between tensile overloads and thermal overloads in order to gain a greater understanding of the material mechanisms at work during thermal overloads.

This thesis details research performed on Hastelloy X at varying temperatures. Chapter 2 describes the experimental methods and details the material and specimen preparation, the experimental procedure involved for both the room temperature and elevated temperature cases, as well as the details behind the multiscale, high temperature digital image correlation (DIC) used in data analysis. Chapter 3 describes the results seen during isothermal fatigue crack closure experiments. The temperature effects on Hastelloy X’s material properties, as well as the details of both the macroscale measurements and microscale measurements of crack closure are also contained within Chapter 3. Chapter 4 explains the results from the thermal jump and thermal overload experiments. A discussion of the results as well as a comparison between tensile overloads and thermal overloads is described here. Chapter 5 concludes the work with all important experimental findings drawn together.
CHAPTER 2

EXPERIMENTAL METHODS

This investigation is concerned with the effects of elevated temperature on fatigue crack closure. Three types of fatigue crack growth experiments were conducted: (i) isothermal, (ii) temperature jump, and (iii) thermal overload experiments. The specimen preparation, materials used, and mechanical loads applied are the same in all three types of experiments. The only difference resides in the temperature profile employed. A description of the experimental methodology followed is provided in this chapter.

2.1 Material and Specimen Preparation

The single edge notch tension (SENT) specimens used in this investigation were 75 mm by 7.0 mm by 1.28 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 100 µm, although profuse annealing twins through the material exist in the majority of grains making the effective average grain size about 50 µm [33]. The chemical composition, as provided by the manufacturer (Haynes International), is given in Table 2.1. The dimensions of the sample were chosen such that the thickness was comparable to companion uniaxial tension specimens, and the width allowed for several millimeters of crack growth. 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 (starting with the coarsest grit and finishing with the finest). A speckle pattern was then applied to the polished surface for the purpose of using the optical technique of Digital Image Correlation (DIC), described in detail in Section 2.3. Two different approaches were used for preparing the speckle pattern, either (a) spray painting the surface with high temperature paint, or (b) applying 1-5 µm Silicon particles to the surface using a compressed air application technique [34][35]. The high temperature paint offers a darker speckle pattern that is more immune to bumps of the sample experienced while being mounted into the load frame. The silicon particles offer a finer pattern making it easier in high temperature experiments to obtain a high quality speckle pattern and lighting conditions. For this reason, for the higher temperature
<table>
<thead>
<tr>
<th>Element</th>
<th>% Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel</td>
<td>47 (balance)</td>
</tr>
<tr>
<td>Chromium</td>
<td>22</td>
</tr>
<tr>
<td>Iron</td>
<td>18</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>9</td>
</tr>
<tr>
<td>Cobalt</td>
<td>1.5</td>
</tr>
<tr>
<td>Tungsten</td>
<td>0.6</td>
</tr>
<tr>
<td>Manganese</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Silicon</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Carbon</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Boron</td>
<td>&lt;0.008</td>
</tr>
</tbody>
</table>

Table 2.1: Chemical Composition of Hastelloy X

experiments, the author used the silicon particles. The high temperature painting method of applying a speckle pattern is similar to the procedure developed by Carroll et al. for room temperature fatigue crack closure experiments on Ti [36].

For the high temperature experiments of interest here, 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 (IR) thermometer to monitor the specimen’s temperature. It has been shown in earlier efforts that this IR thermometer accurately captures the temperature of the specimen and that the temperature is relatively homogenous within the gage section. In order to produce a viable speckle pattern for use in high temperature digital image correlation, the specimen oxidation at raised temperatures must be taken into consideration. The specimen was speckled, the back painted black, and mounted on the load frame. The specimen was then heated with induction coils (described in Section 2.2.1) to the highest temperature the specimen would be exposed to during the experiment (for the thermal jump and overload experiments this refers to $T_2$ which will be explained further in Section 2.2) until a steady state was reached. The coils have been shown to produce a uniform heating across the width of the sample. An example of a speckled specimen taken prior to precracking, with the notch on the left, is shown in Figure 2.1.

This specific method of speckling and then preoxidizing the specimen, prior to testing, works most successfully with Hastelloy X up to about 700 °C. At temperatures exceeding 700 °C, the material begins to glow, which alters the lighting conditions, making DIC correlations across temperatures difficult. In these conditions, the specimen must be painted with a high temperature white paint and then the speckle pattern applied. Running crack closure experiments using this additional white paint is not ideal, as crack tip identification
can be cumbersome if the paint tears at a different rate/location than the specimen cracks. For these reasons, the current investigation chose to restrict itself to temperatures less than, and including, 650 °C.

Temperature dependent material properties for Hastelloy X as provided by Haynes are plotted in Figure 2.2.

Hastelloy X was chosen for this investigation as it retains many of its structural qualities at high temperatures. Table 2.2 shows the elastic modulus and the yield stress of the material as a function of temperature. The yield strength varies by about 130 MPa between the lowest and highest temperatures tested, room temperature and 650 °C respectively. The exact thermal jump and thermal overload experiments, along with their corresponding Case

Figure 2.1: A speckled specimen prior to testing. The notch can be seen at the left.
numbers, are found in Table 2.3.

In order to characterize the crack closure levels of Hastelloy X at elevated temperatures, several experiments were performed under different isothermal conditions. As explained in Section 2.2, for each constant temperature experiment, a fatigue crack was initiated from a machined notch. When the length of the crack reached a total length of between 2.2 mm - 2.4 mm (including the 1 mm notch), measurement cycles were run. Fatigue precracking as well as the measurement cycles were run at the same temperature for each experiment described in this chapter, namely room temperature (RT), 300 °C, and 550 °C. In many cases both macroscale (2 µm/pix, 2x magnification) and microscale (0.4 µm/pix, 10x magnification) experiments were conducted, as described in Chapter 2, Section 2.2.2.

### 2.2 Experimental Procedure

#### 2.2.1 Precracking

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 a 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 from Equation 2.1 for the single edge notch geometry used in this investigation [37], was maintained at $19 \pm 2 \text{ MPa} \sqrt{m}$ by adjusting the load amplitude as the crack length grew. Here,

$$K_I = F\sigma \sqrt{\pi a} \tag{2.1}$$

where $F$ is the dimensionless function given by Equation 2.2, $\sigma$ is the applied stress, and $a$ is the total length of the crack (notch plus fatigue crack). In the expression for $F$, given by

<table>
<thead>
<tr>
<th>Temperature [°C]</th>
<th>Elastic Modulus [GPa]</th>
<th>Yield Stress [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT</td>
<td>205</td>
<td>385</td>
</tr>
<tr>
<td>250</td>
<td>195</td>
<td>325</td>
</tr>
<tr>
<td>300</td>
<td>190</td>
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<td>400</td>
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<tr>
<td>550</td>
<td>175</td>
<td>250</td>
</tr>
<tr>
<td>650</td>
<td>170</td>
<td>250</td>
</tr>
</tbody>
</table>

Table 2.2: Temperature Dependence of Material Parameters for Hastelloy X
\[ F = 0.265(1 - \alpha)^4 + \frac{0.857 + 0.265\alpha}{(1 - \alpha)^2}, \tag{2.2} \]

\(\alpha\) is the crack length divided by the specimen width.

Images were taken during the precracking cycles at a frame rate of 15 fps (8 images per cycle) using a Navitar lens, a Navitar 2x adapter tube, and an IMI Tech IEEE 1394 Digital camera with a 1600x1200 resolution, and then inspected in order to most accurately determine the length of the crack. Lighting was provided by fiber optic gooseneck lights as well as a fiber optic ring light. The camera was connected by firewire to a PC. During the precracking cycles, the load frame and the camera were synchronized by a LabView program and an Instron 8500 PLUS control pad. During loading, the stress ratio \(R\), the ratio of minimum load to maximum load, was maintained at 0.05 as to facilitate the presence of crack closure. Figure 2.3 (a) shows the experimental set up and Figure 2.3 (b) shows a detail of the specimen mounted on the load frame and encircled by the induction coils.

Figure 2.3: (a) An image of the entire experimental set up, excluding the induction heater which is located out of the range of the picture. A close up image of the red, boxed area is shown in (b). (b) A close up showing a specimen mounted on the load frame. The induction coils can be seen surrounding the specimen. Arrows label the various experimental components.
With the crack grown to a total length (including the notch) of between 2.2 mm - 2.4 mm from the edge of the specimen, loading was halted and the specimen was subjected to several cycles run at the same load amplitude as the final cycles of fatigue precracking but at a lower frequency of 0.125 Hz. During these lower frequency cycles, which henceforth will be referred to as "measurement cycles," images were taken at 15 fps (frames per second), totaling 120 images per cycle.

2.2.2 Thermal and Mechanical Loading History

As was mentioned above, this investigation looks at the effects of temperature on fatigue crack closure, in terms of (i) constant elevated temperatures, (ii) thermal jumps, and (iii) thermal overloads. The differentiation between each type of experiment occurred only after fatigue precracking of the specimen produced a total crack length of between 2.2 mm - 2.4 mm. Heating was performed using a Lepel Induction heater to generate currents in the conductive Hastelloy X sample. 3.175 mm copper tubing bent into an elliptical shaped coil and painted with red insulating paint, surrounded the specimen as shown in Figure 2.3 (b). The specimen was heated to its target temperature. Using the IR thermometer attached to a Raytek Thermalert V, specimens were kept within 5°C of the target temperature during all times of testing. A Neslab cooling system connected to cooling coils was used to ensure the load frame’s grips did not overheat. Heating for each type of experiment was performed with the specimen mounted in the load frame and specimens were not removed before testing was completed. As shown in Figure 2.3 (b), the specimen was mounted within the confines of the induction coils while a region of interest was maintained containing the notch and the entire region extending to the right across the specimen from the notch, as it was easy for the coils to obscure this window. The IR thermometer also required a clear view of the center of the specimen from the back.

Adapting the methods of Carroll et al. for room temperature crack closure [36], isothermal experiments were run at temperatures of room temperature, denoted as RT, 300 °C, and 550 °C. The specimen was heated to the desired temperature \(T_1\), fatigue precracking to the optimum crack length was then achieved, and several measurement cycles were completed. The loading profile schematic shown in Figure 2.4 illustrates this, as well as the mechanical history for the thermal jump experiments to be explained next. The precracking regime is shown before the two interrupted lines indicating that many thousands of cycles were performed at \(T_1\) during fatigue precracking. For isothermal closure experiments, following the precracking, several measurement cycles were made at the temperature \(T_1\), as shown by Figure 2.4 following the interrupted lines. DIC was performed during these measurement
cycles with the green dot indicating the zero load image used as the “undeformed configuration” reference image and the blue dots indicating the “deformed configuration” images taken along the loading cycle. This will be further explained in Section 2.3.

Figure 2.4: Schematic of the loading profile. The green dots refer to the image defined as the reference image while the blue dots refer to the deformed images. \( T_1 \) is the temperature used in precracking, the measurement cycles of the constant temperature experiments, and the first round of measurement cycles for the thermal jump experiments. In the thermal jump experiments, the temperature is raised to \( T_2 \) and another few measurement cycles are performed.

Figure 2.4 also illustrates the thermal and mechanical loading for a thermal jump experiment. The first part of the thermal jump experiments were run in the same way as for the isothermal case, including a number of measurement cycles at \( T_1 \). Following the measurement cycles taken at \( T_1 \), the temperature was then raised to \( T_2 \), while the specimen was held in load control at zero load, and another round of measurement cycles were done immediately following the temperature increase. Figure 2.5 shows the mechanical loading for a thermal overload experiment. The procedure was exactly the same as for the thermal jump experiments, except that following the thermal spike and measurement cycles at \( T_2 \), the temperature was lowered back to \( T_1 \), and fatigue cracking was restarted to continue growing the crack. Measurement cycles were completed at various locations as the crack advanced. In this way, crack closure measurements as a function of crack length were made due to the effect of the thermal overload. For these two types of experiments (thermal jump and thermal overload), fatigue crack closure was quantified both at \( T_1 \) and at \( T_2 \), and the closure levels calculated for the \( T_2 \) temperatures could be compared to closure levels at the same temperature during the isothermal experiments. Figure 2.6 explicitly shows the thermal loading schematic for the thermal overload experiments.
Figure 2.5: Schematic of the mechanical loading profile for a thermal overload experiment. $T_1$ is the temperature used in precracking and an initial round of measurement cycles. $T_2$ is the temperature at which the specimen is subjected to a thermal overload during a measurement cycle. Fatigue precracking then continues at $T_1$ and measurement cycles performed at several point as the crack advances.

Typically, 3-5 measurement cycles were run at each temperature to ensure good data collection was obtained (for all experiments performed). The author has shown that no further crack growth occurred during these measurement cycles and no further strain was incurred by the specimen during each successive measurement cycle. This will be experimentally proven in Chapter 4.

Table 2.3 describes the temperatures combinations used during the isothermal, thermal jump, and overload experiments.

2.3 Multiscale High-Temperature Digital Image Correlation

Digital Image Correlation (DIC) analysis of the images taken during the measurement cycles was done using a commercially available digital image correlation software, Vic2D (from Correlated Solutions Inc.). DIC provides a measurement of in-plane displacement and displacement gradient components of a flat, 2D surface. The details of DIC are well known in the literature and are not discussed here [11][12][33]. The method has also been successfully used in the past in high temperature applications. Lyons et al. were among the first to apply DIC to high temperature deformation measurements. They showed accurate DIC displacement and strain measurements up to 650 °C [23]. Grant et al., using “natural contrast
Figure 2.6: Schematic of the thermal profile for a thermal overload experiment. $T_1$ is the temperature used in precracking and an initial round of measurement cycles. $T_2$ is the temperature at which the specimen is subjected to a thermal overload during a measurement cycle. Fatigue precracking then continues at $T_1$.

of the sample” instead of an applied speckle pattern, used DIC to successfully measure the Young’s modulus and coefficient of thermal expansion for a nickel-based superalloy, RR1000, for temperatures up to 1000 °C [24]. Pan et al. calculated the thermal deformation as well as the coefficient of thermal expansion of a chromium-nickel austenite stainless steel specimen at temperatures up to 1200 °C [25].

Here, only the aspects of DIC as related to the high temperature measurements performed in this work, will be discussed. DIC works by tracking the movement of markers, or speckles, on the specimen’s surface between an “undeformed configuration” reference image and a “deformed configuration” image (or multiple images in this case). In this investigation, the point of zero load in each measurement cycle is considered as the reference image, while all other images taken during that measurement are considered deformed. Thus, we are not in general concerned here with strain accumulation between measurement cycles, although such measurements could be made from the images taken during precracking by appropriate choice of an undeformed and a deformed image (i.e., the zero load image of one cycle could be compared with the images taken during loading of a different cycle). In Figure 2.4, the zero load reference image is indicated by the green dot and the deformed images by the blue dots. As demonstrated by Figure 2.7, square subsets are defined in the reference image and the deformation of each subset, assumed to be homogenous, is obtained by correlation with each deformed image.

A minimization method (e.g., Newton-Raphson, BFGS, etc.) on Equations 2.3 and 2.4 is used to find each subset’s corresponding location in the deformed images. This results in a displacement vector for the subset’s center point, defined as the correlation point. The
<table>
<thead>
<tr>
<th>Case No.</th>
<th>$T_1$ [°C]</th>
<th>$T_2$ [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>I1</td>
<td>RT</td>
<td>N/A</td>
</tr>
<tr>
<td>I2</td>
<td>RT</td>
<td>N/A</td>
</tr>
<tr>
<td>I3</td>
<td>300</td>
<td>N/A</td>
</tr>
<tr>
<td>I4</td>
<td>300</td>
<td>N/A</td>
</tr>
<tr>
<td>I5</td>
<td>300</td>
<td>N/A</td>
</tr>
<tr>
<td>I6</td>
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</tr>
<tr>
<td>O1</td>
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<td>650</td>
</tr>
</tbody>
</table>

Table 2.3: Experimental Temperature Combinations. ‘I’ refers to the isothermal experiments. ‘J’ refers to the temperature jump experiments. ‘O’ refers to the thermal overload experiment.

deflection within the subset is assumed to be homogeneous. The expressions for $\tilde{x}$ and $\tilde{y}$ are given by,

$$
\tilde{x} = x_0 + u_0 + du \frac{dx}{dx} \Delta x + du \frac{dy}{dy} \Delta y + \frac{1}{2} du \frac{dx^2}{dx^2} \Delta x^2 + \frac{1}{2} du \frac{dy^2}{dy^2} \Delta y^2 + \frac{d^2 u}{dx dy} \Delta x \Delta y
$$

(2.3)

$$
\tilde{y} = y_0 + v_0 + dv \frac{dx}{dx} \Delta x + dv \frac{dy}{dy} \Delta y + \frac{1}{2} dv \frac{dx^2}{dx^2} \Delta x^2 + \frac{1}{2} dv \frac{dy^2}{dy^2} \Delta y^2 + \frac{d^2 v}{dx dy} \Delta x \Delta y.
$$

(2.4)

Since the subset sizes are decided by the user and the pixel sizes by the resolution of the input images, DIC has no inherent length scale. This allows digital image correlation to be used in both macroscale and microscale applications. Typical subset sizes range from 21x21 pixels to 101x101 pixels depending on the resolution and level of magnification of the images, as well as the quality of the speckle pattern [33].

In order for correlations between the reference subsets and the deformed subsets to be successful, the light intensity must remain constant between the two. A change in the light intensity from the reference subset to the deformed could cause the algorithm to falsely calculate a change in displacement. When a thermal jump or thermal overload experiment was performed, the light intensity distribution of the reference and deformed subsets as a function of $T_1$ and $T_2$ was considered. The light intensity of the subsets must remain constant during the entirety of the test. This becomes more complicated as higher temperatures become involved since metallic surfaces tend to oxidize when heated. The speckle pattern must also adhere to the specimen when heated. Therefore, prior to performing a thermal jump or thermal overload experiment, the specimen was mounted in the load frame and
then preoxidized to the $T_2$ temperature until a steady state of oxidation was reached on the specimen’s surface. The specimen was then cooled to the $T_1$ temperature and precracking was begun.

In this investigation, DIC was performed on images taken at various stages of crack growth in order to determine the exact length of the fatigue crack in the specimen. In addition, using images obtained directly behind the crack tip during the measurement cycles, DIC was used to quantify the effects of crack closure. Carroll et al. used DIC to study the effects of crack closure on Titanium at room temperature [36]. In this investigation, macroscale DIC measurements (using images taken at 2x magnification, 2 $\mu$m/pixel) were used to calculate full-field closure levels of Hastelloy X, while microscale DIC measurements (images taken at 10x magnification, 0.4 $\mu$m/pixel) were used to investigate local crack closure levels in the specimen as a function of distance from the tip of the fatigue crack. Fatigue crack closure was thereby studied as a function of temperature, length scale, and distance from the crack tip.

The microscale measurement cycles (10x) were analyzed using a digital extensometer method. In this method, DIC displacement gages, pairs of individual subsets, were placed on either of the crack. With subset sizes of 71x71 to 101x101 pixels (depending on the resolution of the images), these extensometers measured crack opening and crack closing, at varying locations behind the crack tip, along the length of the crack, as shown in Figure 2.8.

Figure 2.7: Schematic showing the parameters using in mapping a subset in the reference image to a subset in a deformed image [33].
The yellow boxes are the subsets placed on either side of the crack line and are drawn to scale on the figure.

Figure 2.8: Digital extensometers placed at various locations along a crack line. The crack tip is circled in red and then crack is outlined in green. The extensometers are comprised of pairs of yellow-boxed subsets.

The macroscale measurement cycles (2x) were analyzed using a full-field DIC method. Using subset sizes of 41x41 pixels at a spacing of 5 pixels in between subsets, stress intensity factors were calculated using a linear least squares regression method applied to the displacement field. This method allowed for the full-field crack closure level to be calculated. Figure 2.9 shows the regions of interest used in the DIC analysis for both the images taken at 2x magnification and the images taken at 10x magnification. The large red area is the region of interest analyzed in the 2x magnification experiments while the smaller, yellow box is the region of interest analyzed in the 10x magnification experiments. The tip of the initial notch is seen on the left of the zoomed in view as well as on the specimen schematic. The blue box represents the subset size, 41x41 pixels, used during the correlations of the 2x magnification images. Within the yellow box, the crack tip is labeled with a red dot and the digital extensometers are placed along the crack line. In general, during these measurement cycles, the crack is assumed to incur no further growth, a fact confirmed by subsequent analysis, as will be seen later.

Using these DIC methods, two different length scales were considered when analyzing the results shown in the next chapter for constant temperature crack closure experiments. Comparing results from both of these two length scales gives a more complete understanding of the effect of isothermal conditions at elevated temperatures on fatigue crack closure.
Figure 2.9: Schematic of a speckled specimen. The dimensioned specimen is on the left showing the machined notch. The red areas both on the specimen and to the right display the region of interest for the 2x images while the yellow areas display the region of interest for the 10x images.
CHAPTER 3

ISOTHERMAL FATIGUE CRACK CLOSURE

3.1 Macroscale Measurements of Crack Closure, 2x

Macroscale images, taken at 2x magnification, allowed for full-field crack closure levels to be calculated at various temperatures.

3.1.1 Macroscale Analysis Methodology, 2x

Figure 3.1 shows an example of a resulting $v$ displacement field, vertical displacements perpendicular to the crack length, taken at 2x magnification (2 $\mu$m/pix) and analyzed using DIC. At this scale the material response can be described by a macroscopic continuum and therefore, macroscale analysis techniques can be employed. Using a well established method developed for analyzing experimental data acquired through photoelasticity, moiré, and other interferometric techniques, as well as DIC [33], a least squares fit regression was carried out on the $v$ displacement fields output by DIC. A corresponding approach could be done on the $u$ displacement field, the horizontal displacements parallel to the crack length, also measured by DIC, but of much less magnitude than the $v$ displacements.

The fit is done to the first two leading terms in the Williams (1957) asymptotic expansion for stresses and uses four parameters: stress intensity factor ($K$), T-stress ($T$), a rigid rotation ($A$), and a rigid translation ($B$) [38]. The theoretical expression for macroscale displacement fields, assuming a linearly elastic material under monotonic loading, is given by

$$v = \frac{K_I}{\mu} \sqrt{\frac{r}{2\pi}} \sin \left( \frac{\theta}{2} \right) \left[ \frac{1}{2} (\kappa + 1) - \cos \left( \frac{\theta}{2} \right) \right] - \frac{1}{2\mu} \left( \frac{v}{1+v} \right) Tr \sin(\theta) + Ar \cos(\theta) + B, \quad (3.1)$$

where $v$ is the displacement in the $y$ (vertical) direction, $r$ is the distance from the crack tip, $\theta$ is the angle from the crack line ahead of the crack tip, $\mu$ is the shear modulus, $\kappa$ for plane stress is
Figure 3.1: DIC measured $v$-displacements of a specimen during max loading. The scale bar, in pixels, is seen on the right.

$$\kappa = \frac{3 - \nu}{1 + \nu},$$ \hspace{2cm} (3.2)

and $\nu$ is the Poisson’s ratio. Note that the above expression is derived for monotonic loading conditions. Applying it to a measurement cycle of a fatigue crack would imply that the stress intensity factor, $K_I$, found using the regression, is actually the effective change in stress intensity factor, $\Delta K_r$, since the minimum load of each measurement cycle is slightly more than zero ($R > 0$). The effective stress intensity factor range, as defined by Elber and described in Chapter 1 is the difference in the peak of the theoretical stress intensity factor, $K_{\text{max}}$, and the opening stress intensity factor, $K_{\text{open}}$, resulting in Equation 3.3 [1][4]. $K_{\text{open}}$, as shown in Equation 3.4 is thus the difference in the theoretical stress intensity factor, $K_{\text{theor}}$, and the change in the stress intensity factor, $\Delta K_r$, as shown by

$$\Delta K_{\text{eff}} = K_{\text{max}} - K_{\text{open}}$$ \hspace{2cm} (3.3)

$$K_{\text{open}} = K_{\text{theor}} - \Delta K_r.$$ \hspace{2cm} (3.4)

The validity of the 2x magnification results were evaluated by comparing the theoretically predicted KT regression contours (using Equation 3.1) to the experimental contours following the removal of rigid body motion. Figure 3.2 displays a comparison of these two displacement contours for the image corresponding to the maximum load of the measurement cycle for an experiment at 300 °C. The blue solid line displays the experimental vertical displacement
contours while the red dashed line corresponds to the displacement contours output by the KT Regression. The plane-stress Von Mises plastic zone estimate was also shown in Figure 3.2 by the black outline near the individual contour line furthest to the right of the figure. Agreement between the experimental data and Equation 3.1 is very good over the entire field of view, the small discrepancy between them coming from noise due to the equipment necessary for a high temperature experiment. This was verified for all cases of measured stress intensity factors, $K_I$, discussed in this work.

Figure 3.2: Comparison of the experimentally measured $v$ displacement contours and those determined using the KT regression on experimental data.

When analyzing the images taken at 2x magnification, a full-field (macroscale) crack opening and closure level can be calculated by examining a stress intensity factor as a function of load [36]. Fig. 3.3 shows the variation of measured ($\Delta K_r$) stress intensity factor throughout the loading and unloading of a measurement cycle. The theoretical stress intensity factor shown, $K_{theor}$, which has been calculated from a 2D solution, fails to account for the presence of crack closure within the specimen since it is not a result for fatigue crack growth but rather corresponds to monotonic and elastic conditions. The deviation between the theoretical and the experimental $K_I$ curves therefore directly demonstrates the existence of crack closure by reducing the effective stress intensity factor experienced by the crack tip during the fatigue loading cycle. The linear portion of the $\Delta K_r$ curve corresponds to a fully open crack while the portion of the curve with a change in slope denotes the portion of the loading cycle where crack closure is present [36]. The slope of the linear portion of $\Delta K_r$ in most cases agrees with that of $K_{theor}$ demonstrating that once the crack fully opens, the cracked specimen has the predicted compliance, thus indicating primarily elastic deformation outside of the area
of the crack affected by closure. In some cases however, a small error in the estimation of the 
crack tip location may cause differences in the measured and predicted specimen stiffness. Consequently, such discrepancies can cause differences in the maximum value of $\Delta K_r$.

The level of crack closure was then calculated using the “full-field effective K” method
where a line parallel to the $K_{\text{theor}}$ curve is superposed onto the experimental curve and the 
difference between the $K_{\text{theor,max}}$ value and the corresponding value of the $\Delta K_r$ curve divided
by $K_{\text{theor,max}}$ value. This effectively results in a calculation of the percentage of the peak load
that the crack tip experiences [36]. For the purpose of this investigation, unless otherwise
stated, the terms ‘opening’ and ‘closing’ will be used interchangeably.

Figure 3.3: Comparison of theoretical stress intensity factors and those determined using
the KT regression on experimental data at 300 °C.

3.1.2 Room Temperature Fatigue Crack Closure

Figure 3.4 (a) refers to the isothermal Case I1 (found in Table 2.3) at room temperature
and displays the specimen’s $K$ vs. Load plot. Using the “full-field effective K” method, as
described in Section 3.1.1, a closure level of 34% of peak load, $\frac{K_{\text{open}}}{K_{\text{max}}}=0.34$, was calculated. Upon initial loading, the stress intensity factor felt by the specimen gradually increased as
the crack opened. At a point corresponding to the opening of the crack, this stress intensity
factor vs. load relationship became parallel with the $K_{\text{theor}}$ curve.

Figure 3.4 (b) refers to the $K$ vs. Load plot of Case I2 at RT. In this case, the measured
closure level at room temperature was 27% of peak load. The difference in closure values
between the two room temperature measurement cycles could be due to variability between
specimens, which should be expected. Generally, opening load levels for an isothermal case
Figure 3.4: Comparison of theoretical stress intensity factors and those determined using the KT regression on experimental data at RT for Case I1 and I2.

were found to be within $\pm 10\%$, i.e., for RT the measured crack closure values were 30% $\pm 10\%$.

3.1.3 300 °C Fatigue Crack Closure

Figure 3.5 (a) refers to Case I3 run at isothermal conditions of 300 °C. Closure is again seen at this temperature - note the curvature of the applied stress intensity factor at low loads. The calculated closure level for this case was measured at about 19% of peak load. A similar variation in crack closure levels, as was measured for the room temperature cases, was seen by observing the results of the two isothermal 300 °C cases, shown by Figure 3.5 (b) (Case I4 where the measured closure value calculated as 39% of peak load) and Figure 3.5 (c) (Case I5 where the measurement of the crack closure level was 28% of peak load). Taking the spread of $\pm 10\%$ into consideration, the closure levels measured at 300 °C generally agreed with those found at room temperature.

3.1.4 550 °C Fatigue Crack Closure

Moving to slightly higher temperatures, Figure 3.6 refers to Case I6 run at 550 °C. As before, as loading began, the stress intensity factor increased slowly until a certain point when the crack fully opened. Afterwards a linear relationship between $K$ and load was established. The closure level at this temperature was determined as 27% of peak load. Once again,
taking into account the variability involved with crack closure levels, this is very similar to those closure levels calculated for the 300 °C experiments, as well as those calculated at room temperature.

Thus, temperature itself, in an isothermal experiment, does not affect the closure and opening load levels, to an amount greater than can be resolved with the macroscale techniques shown. However, as has been discussed earlier, closure is a very complex and 3D phenomenon that is difficult to distill into one specific load value that is characteristic of an entire sample. The microscale experiments provide a little more insight therefore, into crack closure by furnishing the variation of local opening/closing. The results of microscale
Closure experiments are discussed in the next section.

3.2 Microscale Measurements of Crack Closure, 10x

3.2.1 Microscale Analysis Methodology, 10x

When analyzing the images taken at 10x magnification (0.4 µm/pix), digital extensometers were placed behind the crack tip, on either side of the crack line, as shown in Figure 2.8 [12][11][36]. This procedure was described in more detail in Section 2.3. The amount of crack closure measured is greatly affected by the location of the digital extensometers along the crack line [8]. Each extensometer therefore outputs a different, local closure level and each gage tracks the amount of crack closure occurring as a function of load amplitude and distance from the crack tip. By dividing the load where opening/closing of the crack occurs (the opening/closing load) and the peak load, the amount of local crack opening/closure can be quantified. An example of the locally measured digital extensometer output as a function of the measured load from both loading and unloading during a measurement cycle is shown in Figure 3.7. The opening load is the load at which the gage displacement begins to increase more drastically and the curve’s slope corresponds to the compliance [36]. Figure 3.7 (a) shows the plot from the displacement gage furthest from the crack tip while (b) shows the plot from the displacement gage closest to the crack tip. Note, that in most cases, the opening and closure loads are close, but not exactly the same. We will not be distinguishing between the two unless specifically stated.

3.2.2 Room Temperature Fatigue Crack Closure

As described earlier, in the microscale experiments, each digital displacement gage placed along the crack line in the 10x experiments captures a different local opening and closing load. Figure 3.8 shows the load-displacement results of the isothermal room temperature experiment, Case I1, where four extensometers were placed along the crack length and therefore, four local crack closure measurements were made. The extensometer furthest away from the crack tip was placed at a distance from the tip of 302 µm while the closest extensometer was located a mere 102 µm from the crack tip. The remaining extensometers were placed as indicated in Figure 3.8. The local opening and closing load level increased as the tip was approached, as was expected [36]. Figure 3.9 shows these individual opening and closing levels plotted as a function of distance behind the crack tip. The vertical axis is presented
Figure 3.7: (a) Load vs. Gage Displacement for the displacement gages located at 302 \( \mu m \) from the crack tip and (b) for the displacement gage located at 102 \( \mu m \) from the crack tip at RT.

As the percent of peak load (the ratio of \( K_{\text{open}} \) to \( K_{\text{max}} \) for the opening level and the ratio of \( K_{\text{close}} \) to \( K_{\text{max}} \) for the closure level) while the horizontal axis is the distance of the extensometer from the crack tip (the crack tip being at coordinate \((0,0)\)). As is to be expected, the highest closure levels are seen closest to the crack tip. In fact, furthest from the crack tip the calculated closure level was 42\% of peak load (at 302 \( \mu m \) from the crack tip) while closest to the crack tip the closure level was 67\% of peak load (at 102 \( \mu m \) from the crack tip). The point closest to the crack tip is most shielded by the compressive forces along the flanks of the crack due to the presence of closure and therefore a greater force is required to fully open the crack at that point.

Figure 3.8: Load vs. Gage Displacement curves for the displacement gages located, from left to right, at 302 \( \mu m \), 236 \( \mu m \), 156 \( \mu m \), and 102 \( \mu m \) from the crack tip for a room temperature experiment.
3.2.3 300 °C Fatigue Crack Closure

Digital extensometers were placed on either side of the crack at various locations from the crack tip for the elevated temperature isothermal experiments. Figure 3.10 shows the extensometer placement and the measured results for Case I5 at 300 °C. Six extensometers ranging from 525 µm from the crack tip to 92 µm from the crack tip were used in this experiment. The same unzipping phenomenon was again observed at high temperature as at room temperature. This is shown explicitly in Figure 3.10 which shows the load at which the crack opened/closed in each plot. For each gage placed subsequently closer to the crack tip, the \textit{opening} load measured increased as well (and therefore, the closure level measured increased). Figure 3.11 shows the individual, local opening and closing levels. There is some noise in the load vs displacement curves that increased as the gages approached the crack tip. This is to be expected, as the region closest to the crack tip is subject to the highest compressive forces and the temperature of this experiment is elevated.

For the elevated temperature of 550 °C, no companion local microscale measurements were made, but the results are expected to follow the above stated trends. The microscale experiments showed a more detailed look at the closure phenomenon under isothermal conditions. As the crack tip was approached, the level of crack closure increased. In terms of its dependence on temperature, a spread of ±10% was seen in the general crack closure values between experiments at various isothermal conditions for both the local and global measurements (using the microscale and macroscale analysis methods, respectively). Therefore, the closure phenomenon does not extend into higher temperatures under isothermal conditions and follows the same pattern as observed at room temperature.

Figure 3.9: Local crack closure as a function of distance from the crack tip at room temperature.
Figure 3.10: Load vs. Gage Displacement for the displacement gages located, from left to right on the top: at 525 µm, 412 µm, and 335 µm, and left to right on the bottom: 251 µm, 170 µm, and 92 µm from the crack tip.

Figure 3.11: Local crack closure as a function of distance from the crack tip at 300 °C.
CHAPTER 4

FATIGUE CRACK CLOSURE FOLLOWING THERMAL JUMPS AND THERMAL OVERLOADS

In the previous chapter, it was shown that temperature does not affect crack closure levels in isothermal experiments, at least to within the margins of uncertainty determined for the measurement of closure levels. In a number of experiments, closure levels were seen to vary between 20\% and 40\% of peak load for temperatures between room temperature and 550 °C. Nonetheless, as is clearly shown in Table 4.1, there is a reduction of both elastic modulus as well as yield strength of Hastelloy X over this temperature range, 35 GPa and 130 MPa respectively. Plasticity, being a prominent driving force for crack closure, is affected by temperature. Therefore the hypothesis that crack closure would also be so affected by temperature is reasonable. The question therefore, of whether crack closure is influenced by changes in temperature, remains unresolved. One reason for this is the 3D nature of crack closure \[15]\[39] making it difficult to distill into a single “universal” value of closure/opening load.

As described in Chapter 1, during fatigue cracking, the area in front of the crack tip is affected by competing mechanisms including residual stresses, crack tip blunting, as well as crack closure. Following a tensile overload, the crack tip region experiences compressive residual stresses in an area proportional to the plastic zone size \[31]\[30], which most often cause a retardation of fatigue crack propagation accompanied by an increase in crack closure within this region \[28]\[26]\[27]. Crack tip blunting is also seen \[32]\[30]\[28] and is viewed as a prominent mechanism in the retardation of the fatigue crack’s growth. Thermal overloads/underloads, as well as jumps in temperature could therefore, have a similar effect on crack closure levels. For this purpose, thermal jump and thermal overload experiments were performed in this work. The results of these experiments are discussed in this chapter. As will be seen, although the closure levels are not noticeably affected in isothermal conditions, temperature changes within a single experiment, where uncertainties resulting from sample-to-sample variability (e.g., crack face surface roughness, crack front curvature, local microstructure, etc.) are minimized, have a significant influence on crack closure.

As was previously stated in Chapter 2, Table 4.2 shows the entire array of experiments performed. The isothermal experiments (Case Numbers II-I6) were described in Chapter
### Table 4.1: Temperature Dependence of Material Parameters for Hastelloy X.

<table>
<thead>
<tr>
<th>Temperature [°C]</th>
<th>Elastic Modulus [GPa]</th>
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</tr>
<tr>
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</table>

3. In this chapter, Case Numbers referring to the thermal jump experiments, J1-J4, will be discussed as well as the Case O1, referring to the thermal overload experiment.

To reiterate the procedure outlined in Section 2.2, edge-notched specimens were fatigue loaded in order to initiate and grow a crack at a temperature, $T_1$. Once the crack reached the appropriate length, measurement cycles (cycles run at a slower frequency in order to capture more images during loading and unloading) were performed. For the thermal jump experiments, following the measurement cycles at $T_1$, the sample was maintained at zero load while immediately heated to a more elevated temperature, $T_2$. Measurement cycles were then performed at $T_2$. For the thermal overload experiments, the procedure is exactly the same as just described, except that following the measurement cycles at $T_2$, while at zero load, the specimen was cooled back to $T_1$, and fatigue cracking of the specimen was restarted in order to continue the advance of the fatigue crack. Measurement cycles were done at various points along the growth of the continued crack. Typically, 3-5 measurement cycles were run at each temperature to ensure good data collection. The author has shown

### Table 4.2: Experimental Temperature Combinations. ‘I’ refers to the isothermal experiments. ‘J’ refers to the temperature jump experiments. ‘O’ refers to the thermal overload experiment.

<table>
<thead>
<tr>
<th>Case No.</th>
<th>$T_1$ [°C]</th>
<th>$T_2$ [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>I1</td>
<td>RT</td>
<td>N/A</td>
</tr>
<tr>
<td>I2</td>
<td>RT</td>
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<td>J3</td>
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<td>J4</td>
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<td>O1</td>
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that no further crack growth occurred during these measurement cycles and no further strain was experienced by the specimen during each successive measurement cycle. This will be discussed shortly. From each of these types of experiments, crack closure can be measured as a function of varying types of thermal history.

4.1 Thermal Jump Experiments

4.1.1 Room Temperature to 250 °C Thermal Jump

Starting with a thermal jump experiment from room temperature (RT) to 250 °C, Case J1 in Table 4.2, the room temperature crack closure level was measured to be 27% of peak load. The $K$ vs. load plot obtained from the measurement cycle immediately before the thermal jump took place is shown in Figure 4.1 (a). Following this temperature jump from room temperature (RT) to 250 °C, the specimen no longer experienced any crack closure. As seen from Figure 4.1 (b), the experimental stress intensity factor vs. load curve for the third cycle at $T_2$ is completely linear and agrees very closely with the theoretical curve. The very slight offset between the two curves is most likely due to the theoretical curve beginning at the origin while the loading cycle for the specimen started slightly above zero load (since $R > 0$).

![Figure 4.1: Comparison of theoretical stress intensity factors and those determined using the KT regression on experimental data. (a) $T_1$ of RT. (b) $T_2$ of 250 °C.](image)

In order to prove the assumption that no further crack growth occurred during the successive measurement cycles, along with the assumption that no further strain was incurred by
the sample during this time, the first and third measurement cycles at a given temperature must be compared. Figure 4.2 shows the comparison between the first cycle (a) and the third cycle (b) at the $T_2$ of 250 $^\circ$C. Figure 4.2 (a) showed increased plasticity upon loading (opening) compared to both the theoretical curve as well as the unloading (closing) curve. This increase in plasticity can be explained by Figure 4.3 which shows the vertical strain experienced by the specimen during heating from RT to 250 $^\circ$C at zero load, as well as the decrease in the yield stress. Upon heating, referring to Table 2.2, between $T_1$ and $T_2$ the elastic modulus reduces by 10 GPa while the yield stress reduces by 60 MPa. This decrease in yield stress results in the strain field effectively relaxing, causing strains in the vertical direction to increase. Figure 4.2 (b) however, referring to the third successive measurement cycle, with a purely elastic loading and unloading behavior, proved that no further plasticity was experienced by this additional measurement cycle at 250 $^\circ$C, along with no further crack growth.

![Figure 4.2: Comparison of theoretical stress intensity factors and those determined using the KT regression on experimental data. (a) Cycle 1 at $T_2$ of 250 $^\circ$C. (b) Cycle 3 at $T_2$ of 250 $^\circ$C.](image)

The thermal jump from room temperature to 250 $^\circ$C, a temperature change of roughly 230 $^\circ$C, caused a drastic change in the crack closure levels. A barrage of mechanisms is most likely responsible for the complete disappearance of crack closure following the thermal jump. It was shown that increased plasticity is seen in the first measurement cycle at the elevated $T_2$ temperature and that the reduction in the yield stress of the material could be responsible for the increase in plasticity as well as the elimination of crack closure. The complex interaction of these factors though requires more analysis.

The influence of mechanical overloads on fatigue crack growth rates has been a large area
of research interest. The increased plastic zone size caused by the tensile overload (more specifically by the residual compressive stresses caused by the tensile overload and found just ahead of the crack tip) resulting from the mechanical overload as well as blunting of the crack tip [30][40] have both been proven to reduce crack propagation rates. In fact, Willenberg, Engle, and Wood [41] developed a model where the crack growth rate was assumed to no longer be reduced when the crack had propagated through the plastic zone caused by the tensile overload and Zhao et al. confirmed this experimentally [42]. Elber connected this to the crack closure phenomenon, stating that plasticity-induced crack closure could also be responsible for the transient retardation phenomenon due to overloads, where the elastic region of material surrounding the enlarged plastic zone ahead of the crack tip causes residual compressive stresses thereby reducing crack propagation rates within this plastic zone [1][4]. Following mechanical overloads, crack closure was seen to increase, further protecting the crack tip from damage and thus explaining the retarded crack propagation rates [28][26][32]. Suresh (1983) though, postulated that crack closure could not be the dominant mechanism involved in retarding the crack growth rate following an overload [40].

In analogy to this discussion, the increased size of the plastic zone due to the thermal jumps in these experiments is an important factor in this analysis since an increase in temperature causes a change in the plastic zone size to occur, similar to a mechanical overload. Using the elastic estimate for the radius of the plane-stress plastic zone,

\[ r_{pl-\sigma} = \frac{1}{4\pi} \left( \frac{K_I}{\sigma_y} \right)^2 (1 + \cos \theta + 1.5 \sin \theta)^2, \]  

(4.1)
the plastic zone was plotted as a function of position in front of (and around) the crack tip region [37], and overlaid onto the vertical displacement contours as shown by Figure 4.4. In Figure 4.4 (a), the solid black line shows the plastic zone estimate at the peak load of the third measurement cycle at room temperature while Figure 4.4 (b) shows the plastic zone estimate at the peak load of the third measurement cycle at 250 °C. The solid blue lines and the dashed red lines show a comparison between the experimentally measured DIC, vertical displacement field component and the fitted K-dominant field, respectively. As is to be expected, similar to the case of a mechanical overload, the plastic zone size resulting from the thermal jump from room temperature to 250 °C (shown in Figure 4.4 (b)) is considerably larger than the plastic zone size resulting from the fatigue cracking at room temperature. Note that the plastic zone shapes and sizes are merely representative of those found from the actual experiments. Looking at the large increase in plastic zone size, and following the reasoning of the mechanical overloads described above, one would expect that the increase in plastic zone size following the thermal jump would result in an increase in crack closure since there is now also an increase of residual plasticity surrounding the crack tip region. However, it was clearly seen in Figure 4.1 (b) that in this case, crack closure not only decreased, but was essentially eliminated. In fact, Figure 4.2 (a) showed that the closure was eliminated at exactly the first high temperature cycle. This is because, the closure phenomenon is concentrated directly behind the crack tip rather than in the plastic region shown in Figure 4.4, which is represented ahead of the crack tip. In fact, it has also been seen that in mechanical overload cases, the crack growth rate actually increases for a small amount of crack extension directly following the overload and then decreases significantly as the crack enters the enlarged plastic zone. Thus, to understand why the elimination of crack closure seen here occurs immediately following the thermal jump requires investigation not only of the enlargement of the plastic zone, but also the nature of the opening directly behind the crack tip.

Figure 4.5 shows the strain field in the vertical direction at peak load for both room temperature (Figure 4.5 (a)) and 250 °C (Figure 4.5 (b)). The crack line is found behind the horizontal region of higher strain (shown in red on the scale bar on the right) ending about where the crack tip is found. The plastic zone extends as two lobe-like shapes from the end of the crack tip. As was seen in Figure 4.4 with the black outline of the theoretical plastic zone size, the actual plastic zone is larger at the more elevated temperature.

An optical microscope image of the crack tip region, taken at 50x magnification after the completion of the experiment for Case J1, is shown in Figure 4.6. The black spots are most likely pitting which occurred during polishing of the sample. Note that in this image, the DIC speckle pattern has been removed in order to more accurately view the crack tip.
Blunting of the crack tip and significant opening of the length of the crack are evident as well as branching of the crack away from the final crack tip. This blunting increases the near-tip crack opening displacement which resulted in reduced crack closure. Though the mechanical overload data found in the literature see evidence of blunting as well, as described earlier, in the case of a thermal jump more is at work. During the thermal heating of a specimen, the entire specimen is affected by the increase in temperature and therefore, the entire specimen undergoes changes in its material parameters such as elastic modulus and yield stress. In the case of a mechanical overload, it is the region just in front of the crack tip that experiences the greatest changes. In the case of a thermal heating however, the stress state of the material, along with the stress state of the region of residual compressive stresses, relax. This results in a complete opening of the crack and blunting of the crack tip. The crack tip, no longer considered “sharp” after the first measurement cycle at $T_2$, would now need to reinitiate before closure could reemerge. The enlarged plastic zone should affect the crack growth rate ahead of this overload position as well as the evolution of closure as the crack tip continues to grow through the enlarged plastic zone. The results from a thermal overload experiment, analogous to a mechanical overload experiment in that data is taken prior to, as well as after the overload, will be discussed in Section 4.2.
4.1.2 300 °C to 400 °C Thermal Jump

For Case J2, from Table 2.3, at 300 °C, the specimen experienced a level of crack closure of 19% of peak load. This is shown by Figure 4.7 (a). After the change in temperature of 100 °C (from 300 °C to 400 °C as seen in Table 2.3), which is a less significant jump in temperature than in Case J1, the closure level decreased very slightly, to 18% of peak load. This is shown by Figure 4.7 (b). These two crack closure levels are essentially the same within the resolution limits of the measurement techniques. This suggests that a temperature jump of 100 °C is not sufficient to affect the level of crack closure measured. From the material property values shown in Table 2.2, one can see that the elastic modulus reduces by 5 GPa while the yield stress reduces by 20 MPa when the temperature jumps from 300 °C to 400 °C (compared to 10 GPa and 60 GPa due to the jump from RT to 250 °C in Case J1).  

Figure 4.8 shows the crack tip region of a specimen following the completion of the Case J2 experiment at the $T_1$ of 300 °C and at the $T_2$ of 400 °C. Looking at a microscope image of the notch region, the actual plastic zones are visible upon the deformed surface of the specimen. The initial notch is visible, as well as a bit of crack growth extending from the notch that has widened during further crack growth due to the fatigue loading of the specimen. The actual crack tip however, is not visible and seemingly no crack tip blunting has occurred.  

Looking at a microscope image of the crack tip region following the completion of the experiment for this Case J2, the crack line is not visible past the initial notch. Figure 4.9 shows a 5x magnification view of Case J2. The speckle pattern has been cleaned as well as possible and the crack line is completely hidden. After finishing the experimental procedure for Case J2 as described above, the author continued to grow the fatigue crack at 400 °C
for another 0.5 mm. However, the initial blunting that could have occurred at the time the thermal jump occurred would still be visible. A possible explanation for this is that the “sharp” fatigue crack grown at 300 °C never blunted when the temperature was raised to 400 °C. In the Figure 4.9, the bright white area is the plastically deformed zone ahead of the crack tip following the fatigue cracking at 300 °C and the thermal jump to 400 °C. The crack was then grown, as stated previously, another 0.5 mm past this plastic zone. As is evident however, no crack line or crack tip is visible in the image.

4.1.3 300 °C to 550 °C Thermal Jump

Figure 4.10 shows the $K_I$ vs load before and after the thermal jump for Case J3. In this case, the specimen experienced a crack closure level of 39% of peak load at the initial temperature, $T_1$, of 300 °C (Figure 4.10 (a)). When the temperature was jumped to the $T_2$ temperature of 550 °C, the closure level reduced to 15% of peak load (Figure 4.10 (b)). Compared to the other specimens tested at 300 °C, Case J3 had a higher level of crack closure (as discussed in Section 3.1.3). Taking only this specimen into consideration though, thereby eliminating the variability between specimens, the reduction from 39% to 15% of peak load was significant. This drop in closure level is more than was seen for the thermal jump from 300 °C to 400 °C where no change in closure occurred. The temperature change from $T_1$ to $T_2$ is accompanied
Figure 4.7: Comparison of theoretical stress intensity factors and those determined using the KT regression on experimental data. (a) $T_1$ of 300 °C. (b) $T_2$ of 400 °C.

by a reduction in the elastic modulus of the material of 15 GPa and in the yield stress of 50 MPa. The temperature difference of 250 °C was the same for Case J1 ($T_1$ was RT while $T_2$ was 250 °C), as described in Table 4.2. In Case J1, however, following the temperature jump of 250 °C, no further crack closure was measured. Consequently, only considering the change in temperature between $T_1$ and $T_2$ is not an adequate metric in predicting the amount of crack closure that will result. Considering the material properties between Case J1 and J3, Case J3 experienced only a 50 MPa reduction in yield stress with the temperature jump while Case J1 experienced a 60 MPa reduction. Case J3 experienced a more pronounced decrease in the elastic modulus compared to Case J1 though. All of these material parameters, along with the change in temperature, the change in the plastic zone in front of the crack tip, the crack opening displacement must be taken into account when analyzing the difference in crack closure levels between cases.

The plastic zone directly ahead of the crack tip can be estimated for 300 °C in this case to be roughly 0.573 mm. The corresponding value at 550 °C is 0.852 mm. This results in a change in plastic zone size of 0.252 mm due to the temperature jump for Case J3. Similarly, at RT the plastic zone size can be estimated to be 0.348 mm and at 250 °C to be 0.488 mm, resulting in a change in plastic zone of 0.14 mm due to the temperature jump shown by Case J1. Comparing Cases J1 and J3, Case J1, as discussed in Section 4.1.1, resulted in the elimination of crack closure following the thermal jump while Case J3 resulted in the reduction (not elimination) of closure, even with a larger change in the size of the plastic zone. A more significant change in the size of the plastic zone ahead of the crack tip therefore does not directly determine whether or not closure will be eliminated completely. Thus, the change in the plastic zone size alone is also not an adequate metric in predicting the amount
of crack closure that will result from a thermal jump.

The maximum plastic zone size can be seen in the plot of the vertical strain field at maximum load in Figure 4.11, where (a) shows the strain field at 300 °C while (b) shows the strain field at 550 °C. As estimated above, the plastic zone size is larger at 550 °C than it is at 300 °C.

The crack tip image, taken at 50x magnification of a specimen used in Case J3, showed (as was also shown in Section 4.1.1) possible blunting as well as branching of the crack tip as seen in Figure 4.12. The jump from 300 °C to 550 °C (Case J3) does not cause the same dramatic opening and blunting of the crack tip as did the jump from room temperature to 250 °C (Case J1), though more so than the jump from 300 °C to 400 °C (Case J2). Still, this increased crack opening displacement along with the relaxation of the stress state of the material due to the decrease in the yield strength caused the reduction in crack closure.

4.1.4 300 °C to 650 °C Thermal Jump

For Case J4, a $T_1$ of 300 °C resulted in a closure level of 28% of peak load as shown in Figure 4.13 (a). $T_2$ was chosen as 650 °C in order to create a temperature change greater than 300 °C and to keep one of the changes in material parameters constant compared to the previous Case, J3. The elastic modulus between 300 °C and 650 °C decreases by 20 GPa while the yield stress decreases by 50 MPa. The change in yield stress is therefore the
same in both Case J3 and Case J4. Following the temperature jump however, unlike for Case J3, Case J4 experienced a complete elimination of crack closure as shown in Fig. 4.13 (b), similar to the room temperature to 250 °C thermal jump (Case J1). Considering solely the change in yield stress of the material between $T_1$ and $T_2$ is therefore also not an adequate metric for predicting the resulting crack closure levels. Comparing Case J1 and J4 (which both experienced an elimination of crack closure), the elastic modulus decreases by 10 GPa and 20 GPa respectively. The yield stress decreases by 60 MPa for Case J1 and by 50 MPa for Case J4. Case J4 therefore, experienced a smaller decrease in the yield stress but a larger decrease in the elastic modulus compared to J1. Yet, following the thermal jump, neither J4 nor J1 experienced crack closure.

Figure 4.14 (a) shows the vertical strain field at peak load at 300 °C for Case J4 while Figure 4.14 (b) shows the vertical strain field at peak load at 650 °C for Case J4. The data is slightly noisier in this plot than in the corresponding figures from the other thermal jump experiments. This is because, during preoxidation at 650 °C, the grains were exposed due to the elevated temperature. Still, as was evident before, the plastic zone size is seen to enlarge after the thermal jump to 650 °C.

This thermal jump, as seen in previous cases, caused blunting of the crack tip as seen in Figure 4.15. Blunting, as discussed earlier, was also seen following the thermal jump from 300 °C to 550 °C, but without the complete elimination of crack closure. In order to
Figure 4.10: Comparison of theoretical stress intensity factors and those determined using the KT regression on experimental data. (a) $T_1$ of 300 °C. (b) $T_2$ of 550 °C.

establish whether a “degree of blunting” could explain this discrepancy, very precise imaging and analysis of the crack tip is needed. Within the constraints of the analysis methods used in this investigation, this “degree of blunting” cannot be readily determined.

4.2 Thermal Overload Experiment, 300 °C to 650 °C

A thermal overload experiment is thought to be analogous to a mechanical overload experiment where a fatigue crack is grown at a given load, a tensile overload is performed, and then crack growth is continued post-overload. Typically, as previously explained in Chapter 1, factors such as crack closure and crack growth rates are considered post-overload. Crack growth rates have been seen to decrease while crack closure levels have been seen to increase following the overload and the growth rates have been experimentally proven to reach nominal, pre-overload levels, as soon as the crack has grown a certain distance from the point of overload [30][28][42].

In the thermal overload experiment performed in this work, Case O1 in Table 4.2, the crack was grown at a $T_1$ of 300 °C until a total crack length of 2.16 mm was reached, a thermal overload at a $T_2$ temperature of 650 °C was performed at this same crack length, and finally, crack growth was continued at $T_1$. Crack closure was quantified at various locations while growing the fatigue crack post-overload by performing a few measurement cycles (a reduced frequency cycle) periodically as the crack advanced. At the overload temperature of 650 °C, no crack closure was measured (as also shown earlier with a thermal jump from 300 °C to 650 °C in Section 4.1.4). This overload result can be seen in Figure 4.16 which shows the
DIC measured $K_I$ vs load history of the third thermal overload cycle. As stated before in section 2.2.2, typically three to five measurement cycles were run at each temperature. In the thermal overload experiment discussed here, three measurement cycles were run each time crack closure was quantified. The closing and opening parts of the experimental curve are labeled in the figure. Increased global plasticity due to the lowered yield stress at this higher temperature, made evident by the nonlinearity induced in the $K_I$ vs load curve, in this case at higher loads, accounts for the difference between the opening and the closing curve.

A comparison of the first and third measurement cycles taken at 650 °C as was done for the room temperature to 250 °C thermal jump in Section 4.1.1, can be seen in Figure 4.17. Opening and closing curves are labeled. Figure 4.17 (a) shows the first measurement cycle performed after the temperature was raised to the $T_2$ of 650 °C. A large amount of plasticity can be seen upon loading (opening) of the specimen though crack closure is seen to be eliminated in this first measurement cycle (as was seen in Section 4.1.1 when analyzing the measurement cycles taken at 250 °C). This large amount of plasticity is caused by the thermal heating of the sample from 300 °C to 650 °C. Figure 4.17 (b) shows the third measurement cycle taken at 650 °C (and shown previously as Figure 4.16). Unlike what was seen in Section 4.1.1 in the third measurement cycle (Figure 4.2 (b)), Figure 4.17 (b) displays evidence of further plasticity in this third measurement cycle, though much less pronounced than in the first. Once again, this can be attributed to the thermal jump from 300 °C to 650 °C leading to a more relaxed stress state within the entire specimen. The assumption of no further crack growth upon successive measurement cycles is still valid as the increase
in plasticity measured in the third measurement cycle at 650 °C was so much less than that of the first cycle at that temperature.

Following the overload, the fatigue crack growth of the specimen was continued at $T_1$ and crack closure was quantified at five different locations corresponding to total crack lengths (including the notch) of: $a = 2.22$ mm, $a = 2.39$ mm, $a = 2.5$ mm, $a = 2.68$ mm, $a = 2.76$ mm, and $a = 3.08$ mm. The final crack length was chosen as it was calculated to be outside of the increased plastic zone created by the overload cycle at 650 °C (the plastic zone was estimated to be a total of 0.825 mm in front of the crack tip following the thermal overload). Figure 4.18 shows the $K_I$ vs. load plots at each of these crack lengths. Figure 4.18 (a) shows the $K_I$ vs load curve measured at a total crack length of 2.22 mm which corresponds to a growth past the overload point of 0.064 mm. The level of crack closure quantified here was 10% of peak load. Figure 4.18 (b)-(d) then show crack closure levels at various points along the advancing fatigue crack. The level of crack closure is seen to gradually increase as the crack advances from 10% to 48%. Unlike after a mechanical overload, as previously discussed 48% of peak load, crack closure was drastically retarded following the thermal overload. As crack growth continued, the amount of crack closure gradually returned to a more “typical” level for the $T_1$ temperature of 300 °C.

Adapting the typical $da/dN$ vs. $a$ plots used in analyzing mechanical overloads (where $da/dN$ is the crack growth rate and $a$ is the total length of the crack), Figure 4.19 shows the closure level (as percent of peak load) as a function of crack length for the overload
Figure 4.13: Comparison of theoretical stress intensity factors and those determined using the KT regression on experimental data for Case J4.

The shown closure levels were all measured at 300 °C following the thermal overload occurring at \( a = 2.16 \text{ mm} \), denoted by the vertical line. No measurement cycle was performed at 300 °C immediately following the thermal overload. A light green shaded region has been overlaid to show the closure level typically found in isothermal 300 °C experiments (30% ±10%) without the effects of a thermal jump or overload. As fatigue crack growth rates have been shown to return to nominal, post-overload levels when grown outside of the effected plastic zone caused by a tensile overload, the closure level gradually increased as the fatigue crack was grown past the overload point. Figure 4.20 shows a crack length, \( a \), vs. number of cycles, \( N \) curve. The blue line displays the data points from the experimental crack length vs. number of cycles. Each data point was taken after approximately the same amount of crack advance. The dashed red line represents the crack length, \( a = 2.1596 \text{ mm} \), where the thermal overload occurred and the dashed green line represents the crack length, \( a = 2.9846 \text{ mm} \), where the crack should have (based on a calculated estimate from Equation 4.1) grown out of the enlarged plastic zone created by the thermal overload of 650 °C. Unlike in mechanical overload experiments where the crack growth rate increases for a few cycles and then decreases following an overload, Figure 4.20 shows a gradual decrease in crack growth rate until a little before the estimated boundary of the elasto-plastic zone when the crack growth rate increased again. For a mechanical overload, this retarded crack growth rate is often due to an increase of crack closure, thereby shielding the crack tip from further deformation. In this case of a thermal overload however, crack tip blunting leads to the change in crack growth propagation rate. The blunted crack needed to reinitiate before further growth could occur.
Figure 4.14: (a) Vertical strain field at maximum load at 300 °C. (b) Vertical strain field at maximum load at 650 °C.

Figure 4.15: Post-mortem image of a crack tip at 50x magnification for Case J4.
Figure 4.16: Comparison of theoretical stress intensity factors and those determined using the KT regression on experimental data at $T_2$ of 650 °C for Case O1. The opening and closing curves are labeled.

Figure 4.17: Comparison of theoretical stress intensity factors and those determined using the KT regression on experimental data. (a) Cycle 1 at $T_2$ of 650 °C. (b) Cycle 3 at $T_2$ of 650 °C. Case O1
Figure 4.18: Comparison of theoretical stress intensity factors and those determined using the KT regression on experimental data for various crack lengths. The vertical line defines the point at which the thermal overload occurred. (a) $a = 2.22$ mm, closure level of 10% of peak load, (b) $a = 2.39$ mm, closure level of 24% of the peak load, (c) $a = 2.50$ mm, closure level of 22% of the peak load, (d) $a = 2.68$ mm, closure level of 28% of peak load, (e) $a = 2.76$ mm, 40% of peak load, and (f) $a = 3.08$ mm, closure level of 48% of peak load.

Figure 4.19: Comparison of theoretical stress intensity factors and those determined using the KT regression on experimental data for various crack lengths. (a) $a = 2.22$ mm, (b) $a = 2.39$ mm, (c) $a = 2.50$ mm, (d) $a = 2.68$ mm, (e) $a = 2.76$ mm, and (f) $a = 3.08$ mm.
Figure 4.20: $a$ vs. $N$ for Case O1 at 300 °C. The red dashed line signifies where the thermal overload to 650 °C occurred and the green dashed line signifies where the crack should have grown out of the plastic zone created by the thermal overload.
This investigation provided a multiscale examination of the effects of temperature on fatigue crack closure levels of Hastelloy X. Hastelloy X was chosen for the investigation due to its high temperature, structural qualities. In order to obtain a complete understanding of the effects that temperature has on fatigue crack closure, three different experiments were performed: (i) isothermal experiments at RT, 300 °C, and 550 °C, (ii) thermal jump experiments with temperature jumps from RT to 250 °C, 300 °C to 400 °C, 300 °C to 550 °C and 300 °C to 650 °C, and (iii) thermal overload experiment from 300 °C to 650 °C.

Two different length scales were considered, each using a different digital image correlation analysis methodology. Macroscale DIC measurements at 2x magnification (2 µm/pix) provided full-field crack closure measurements according to the methodology developed in Section 3.1. In this method, stress intensity factor vs load curves allowed for the calculation of opening/closing loads and therefore, the calculation of crack closure. Local crack closure measurements, as a function of distance behind the crack tip, were obtained using microscale DIC measurements at 10x magnification (0.4 µm/pix). Here, digital extensometers were placed at various points along the crack line, behind the crack tip. As the specimen was loaded and unloaded, each extensometer measured the opening and closing of the crack at a different distance from the crack tip. This allowed local closure/opening loads to be determined for each isothermal condition.

The macroscale, isothermal experiments were unable to show a significant temperature effect on the crack closure levels measured at each temperature, in the temperature range considered here (RT to 650 °C) and within the resolution obtained. From a significant number of isothermal closure measurement experiments conducted at 300 °C and at room temperature, sample variability within the same temperature resulted in crack closure levels of 30% ±10% of peak load. This same result was obtained between samples tested at different isothermal conditions as well.

The microscale, isothermal experiments showed similar results. As was expected, the points along the crack line that were closest to the crack tip were most shielded by the compressive forces along the flanks of the crack due to the presence of closure and therefore,
a greater force was required to fully open the crack at those locations [36]. This resulted in the highest level of crack closure being measured closest to the crack tip for both room temperature and high temperature. Furthest from the crack tip however, fewer compressive forces fought against the loading of the specimen and therefore, a lesser force was needed to open the crack. Lower levels of crack closure were measured at the points furthest from the crack tip for both room temperature and high temperature. The crack was seen to “unzip” during the loading cycle in all isothermal conditions. Also, the local crack closure/opening measurements agreed between the room temperature results and the high temperature results with a difference in between specimens and in between temperatures of ±10% as was shown in the macroscale measurements. It was therefore proven, that within the resolution measured through the macroscale and microscale techniques, temperature itself did not affect the closure and opening load levels.

Plasticity, being a prominent driving force for crack closure, has a strong temperature dependence. Therefore, the investigation was extended to thermal jumps. Crack closure was measured at the initial temperature condition under which the crack had been fatigue loaded, as well at the elevated temperature. When analyzing the crack closure levels of these thermal jump experiments, crack tip opening, the change in plastic zone size, as well as the change in material parameters were all considered. In such a configuration, the sample-to-sample variability was eliminated.

From the jump from 300 °C to 400 °C, where the amount of crack closure reduced by 1%, it was determined that a temperature change of 100 °C was not enough to cause any change in the crack closure levels measured. From the jump from RT to 250 °C where the amount of crack closure reduced from 27% of peak load to 0% of peak load (i.e., closure was completely eliminated), and the jump from 300 °C to 550 °C where the amount of crack closure reduced from 39% to 15% of peak load, it was determined that although temperature does affect closure levels, only considering the change in temperature between \( T_1 \) and \( T_2 \) was not an adequate metric in predicting the amount of crack closure that will result.

Considering another aspect of these thermal jump experiments, for the RT to 250 °C jump, the yield stress was reduced by 60 MPa while for the 300 °C to 550 °C jump, the yield stress reduced by 50 MPa. However, the 300 °C to 550 °C experienced a larger decrease in the elastic modulus than the RT to 250 °C jump, implying that the change in the plastic zone size upon thermal jumping was larger for the 300 °C to 550 °C jump. Finally, crack tip opening between the two cases was considered and the RT to 250 °C jump caused more significant crack tip blunting (as shown by post-mortem visual inspection in Figure 4.6 and Figure 4.12) than the jump from 300 °C to 550 °C. This blunted crack, no longer considered to be sharp, would need to reinitiate before closure could reemerge.
This is possibly advantageous towards delaying continued fatigue crack growth although the elimination of crack closure normally would increase crack growth rate, the delay resulting from the necessity to reinitiate a sharp fatigue crack may be considerable. Between the 300 °C to 550 °C jump and the 300 °C to 650 °C jump, where crack closure reduced from 28% to 0% of peak load, the change in yield stress was kept constant. Solely considering the change in yield stress is therefore also not an adequate metric for predicting the amount of crack closure that will result from a thermal jump. Consequently, the interplay between these mechanisms was determined to be very complex and temperature dependent.

In the thermal overload experiment, closure was seen to be about 10% of peak load, following the thermal overload of from 300 °C to 650 °C, but was then seen to gradually increase as the fatigue crack advanced again at the original 300 °C temperature. Once the fatigue crack was deemed to be out of the region of the enlarged plastic zone resulting from the thermal overload, the final crack closure measurements were made. The final crack closure level was calculated at 48% of peak load. Since crack growth rate is such a significant part of the analysis done for mechanical overloads, an \( a \) vs. \( N \) curve, Figure 4.20, was plotted from the thermal overload experimental data. This curve showed severe crack growth rate retardation following the overload which seemed to increase slightly once the crack had grown out of the affected plastic zone. Though an increase in crack closure accompanied this growth rate retardation (contrary to the effects of a mechanical overload), crack tip blunting was determined to explain both phenomenon. The blunted crack tip needed to reinitiate before further growth could occur.

In summary, the current work used macro- and microscale digital image correlation techniques to study fatigue crack closure under varying thermal conditions. Competing mechanisms were shown to be at work. While isothermal conditions were proven to have little effect on crack closure levels measured, both thermal jumps and thermal overloads dramatically affected the fatigue crack closure. While the change in yield stress, elastic modulus, plastic zone size, and temperature caused by the jump in thermal conditions all contributed, the crack tip opening behavior was shown to play the dominant role in reducing or eliminating fatigue crack closure.

One avenue of future work is modeling of the current experiments. If the thermally dependent nature of crack closure observed here was integrated into a material model, important advancements could be made in the prediction of thermomechanical fatigue behavior and eventual failure of components at high temperatures and in the presence of thermal jumps and overloads.

The connection between temperature dependent fatigue damage associated with crack growth in ductile metals and microstructure could also be further investigated. With higher
resolution measurements, such as those performed by Carroll (2011) [33] or also even as described in Section 3.2, the degree of crack tip blunting could be established, shedding more light onto this dominant mechanism. An investigation of fatigue crack growth and closure at varying temperatures (up to 1000 °C), performed with combination ex situ/in situ DIC techniques could help to quantify fatigue damage, and relate it to grain geometry and orientation on a full-field basis. Accumulated deformation at a material point is dependent on a combination of grain geometry, orientation, position, and temperature in relation to the crack line. The microstructural dependence on fatigue crack growth and crack closure could be elucidated with grain geometry information. This could be accomplished through Electron Backscatter Diffraction (EBSD) measurements which could serve to relate measured strain with local microstructure. EBSD analysis would obtain microscale information so that it could be determined where individual grain behavior becomes an important factor in the fatigue response of a material.
REFERENCES


