Creep-Fatigue Crack Growth Using Digital Image Correlation

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Abstract Creep-fatigue crack growth tests are cyclic tests that have a hold period at the maximum load. This hold period, or dwell, is the period during the test when the time-dependent mechanisms operate. The length of the dwell period has been shown to affect the fatigue crack growth rate. During the hold period, crack tip blunting (due to creep deformation) and crack extension can be measured using 2-D digital image correlation (DIC). DIC requires a random speckle pattern on the flat surface being investigated. The speckle pattern is a unique pattern and, as the surface is strained, locations on the pattern will move to new positions relative to a previous strained condition. The images are compared and an algorithm calculates the strain. The camera can be positioned to view the crack tip and measure crack extension and crack opening displacement (COD). This provides a means by which the crack tip creep deformation can be determined during the hold period, providing valuable information regarding the crack tip kinetics and crack driving force. This paper will evaluate this technique for creep-fatigue crack growth measurements and provide preliminary data for a Ni-base alloy.

Keywords Creep-Fatigue, Crack Growth, Digital Image Correlation

1. Introduction

A number of important industrial applications require materials to be subjected to elevated temperatures, cyclic stresses, and potentially aggressive environments. Creep-fatigue occurs when a combination of these conditions are present. During the dwell period of a creep-fatigue cycle, several damaging effects at the crack tip can take place causing an increase in the crack growth rate. The crack tip driving force therefore could be influenced by a number of active processes, such as oxidation, oxygen diffusion, and creep deformation [1]. Understanding the kinetics of these various processes is essential to predicting the behavior of a material under creep-fatigue conditions [2]. Some studies and techniques have been proposed to evaluate the rates of these processes [3]. It is quite challenging to experimentally disassociate the different processes and arrive at the exact contribution provided by each process. Oxygen diffusion along the grain boundaries is clearly a culprit in embrittling some materials such as nickel-base alloys [4]. This diffusional process is, in part, driven by the crack tip stress. Rapid stress relaxation, therefore, has been proposed to reduce the crack growth rate [5]. Quantifying the re-distribution of stresses and strains at the crack tip is critical to predicting the crack growth rate during creep-fatigue.

One technique developed in the last 25 years that could be used to help interrogate the crack tip during creep-fatigue is digital image correlation [6]. This noncontact experimental technique allows for the observation of the strains using an image analysis technique [7]. The surface of a test specimen has to be prepared, having a unique speckle pattern. The random speckles are then used as reference points for determining amounts of displacement and strain measurements to be calculated with respect to a starting reference image. This technique has been used to determine crack tip displacements during creep crack growth as well as fatigue crack growth. This paper gives some preliminary results using a 2-D digital image correlation system to determine the crack tip displacements and crack growth rates for the nickel alloy Hastelloy X at elevated temperature with creep-fatigue conditions.

2. Experimental Procedure

The material used in this study was Hastelloy X (see Table 1 for the chemical composition), which was acquired in the annealed condition in the form of a cold finished plate with a thickness of 6.35mm. From this plate a sample was removed in the T-L orientation for the creep-fatigue test.

Table 1. Nominal chemical composition of Hastelloy X in weight %

Alloy	Ni	Fe	Cr	Mo	Cu	Co	W	Ti	C	Mn	Si	Al	Other
Hastelloy X	Bal.	18	22	9	<0.50	1.5	0.6	<0.15	0.1	<1	<1	<0.5	<0.08

From this plate a sample was removed in the T-L orientation for the creep-fatigue test with the geometry shown in Figure 1.

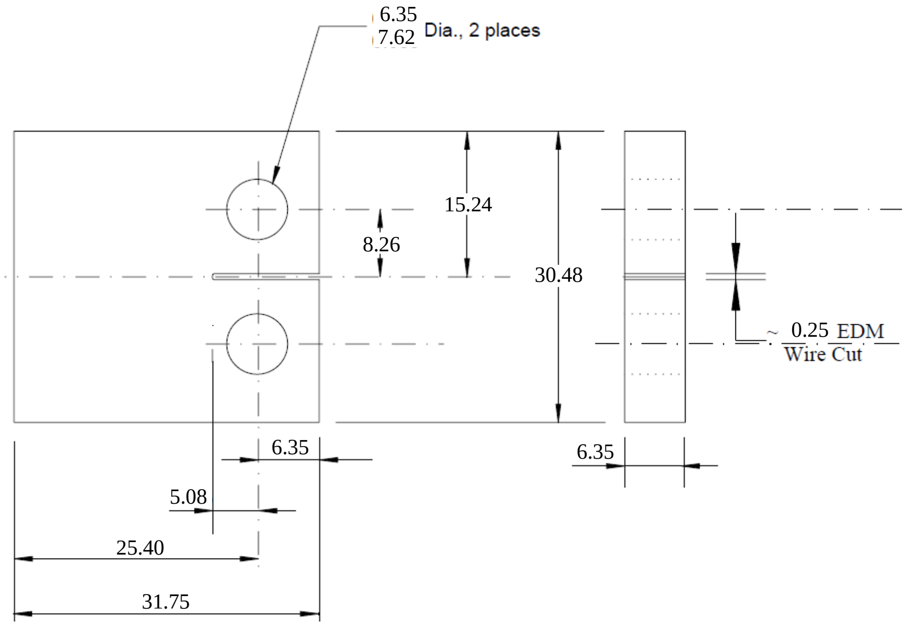

Figure 1. Creep-fatigue specimen geometry (dimensions are in mm)

The specimen was then prepared for the noncontact digital image correlation. A high contrast random, speckle pattern was applied in two steps. First a flat white high temperature ceramic based coating (VHT Flame Proof^{TM}) was applied to one surface of the specimen. After the coating had dried, a mist of a flat black high temperature coating was sprayed over the white coating layer to provide the contrasting speckle pattern.

The specimen was fatigue pre-cracked for ~2.5mm, ending with ΔK = 27.6 MPam$^{1/2}$. The fatigue pre-cracking and creep-fatigue test were conducted using a 100kN MTS servo-hydraulic test system. The creep-fatigue test was performed using a trapezoidal waveform with a 1.5 second ramp up, a 120 second dwell at max load, and a 1.5 second ramp down. A loading ratio of R=0.05 was used. The test was conducted in laboratory air at 650ºC ± 3 ºC. The elevated temperature was applied using a 1.2kW Ameritherm induction heater and monitored using a two-color optical infrared thermometer.

The Correlated Solutions Vic-2D digital image correlation system was used to capture images and analyze crack tip displacements. Images were captured at a rate of ~6 images per second using a 5MP Point Grey camera. Images were captured for only a few cycles at a time collecting ~730 images per cycle.

3. Results and Discussion

3.1. Crack tip strain

The displacement measurements and strain calculations presented herein were performed for cycles number 9 and number 62 during the creep-fatigue test. The measurements were made with respect to an unloaded reference image. The strain measurements were made on a small region around the crack and crack tip as is shown in Figure 2.

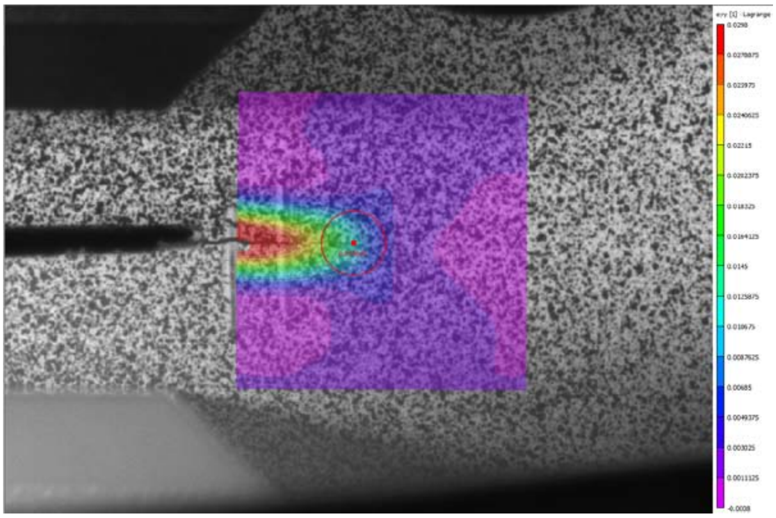

Figure 2. Representative image of the digital image correlation strain calculation. Inside the red circle is the region around the crack tip that was used for the strain measurements.

The crack tip strain was measured for the 120 second hold period of cycle 9 and cycle 62 of the creep-fatigue test using the region contained by the red circle in Figure 2. The strain was calculated for the y-direction using the Lagrange tensor, and the results for cycles 9 and 62 are shown in Figure 3.

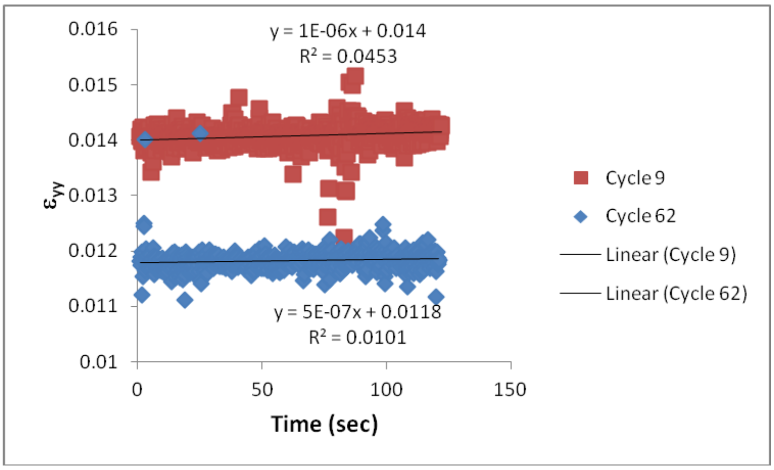

Figure 3. The crack tip strain during the creep-fatigue hold period for cycles 9 and 62.

During the hold period the strain measured had some noise present in the ~730 data points used for each cycle. This may be due to the thermal effect on the air between the camera and the sample. Nevertheless, a small positive slope was the trend for both cycles. Therefore a crack tip creep rate for this 120 second period was determined. During cycle 9 the creep rate was $1x10^{-6}$ and it was $5x10^{-7}$ during the hold period of cycle 62. This at least indicates that a crack tip creep rate can be measured on this material at 650ºC for a 120 second hold period using digital image correlation.

Also, the results showed that the magnitude of the strain is higher for cycle 9 than cycle 62. It is not clear what has produced this result. It may be that the images were taken with a resolution too low to accurately see the crack tip. Therefore, when the local selection was made to extract the data from the crack tip, the exact location may have differed between the two cycles.

3.2. Crack Opening Displacement (COD)

COD measurements were also measured for cycles 9 and 62. These measurements were made relative to the unloaded reference image. A linear measurement of COD was performed across a small region within the selected area shown in Figure 4.

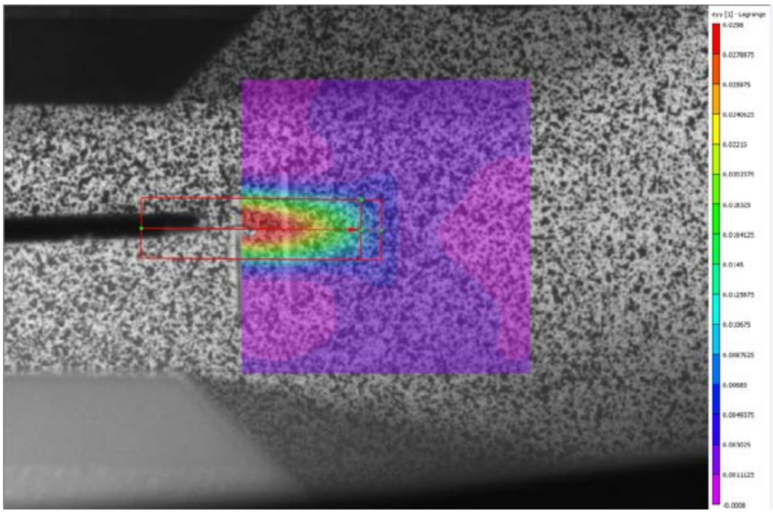

Figure 4. The crack opening displacement measurement was made along a linear region shown in the red rectangular box.

COD data (in pixels) was then extracted at a location across the EDM notch (i.e. the far left point in the red rectangle shown in Figure 4). The COD data was taken from the beginning (the first two seconds), the middle (seconds 60 and 61), and the end (seconds 119 and 120). The twelve data points at each location were then averaged. The results are shown in Figure 5.

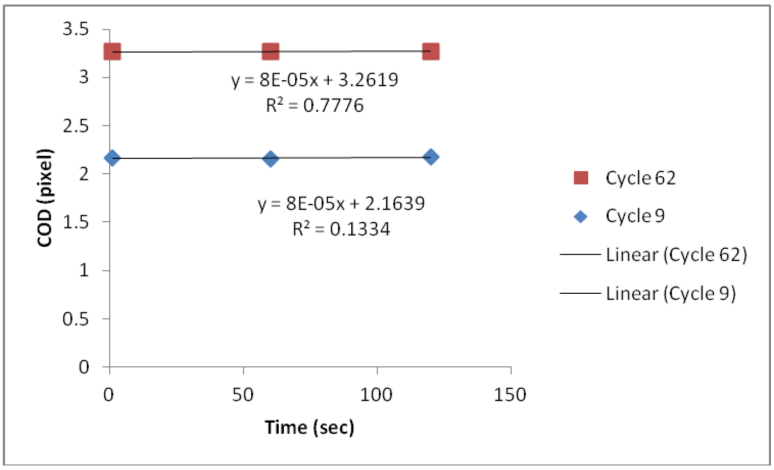

Figure 5. The COD measurements during the creep-fatigue hold period for cycles 9 and 62.

The COD measurements were clearly higher for cycle 62 than for cycle 9. This is what would be expected, since at a later point in the test the crack would have grown causing a larger COD measurement. Also, for both cycles the slope is positive, indicating that the crack opening increased during the hold period.

4. Conclusions

DIC was used to measure both the crack tip deformation and crack opening displacement during a 120 second hold period of a creep-fatigue crack growth cycle. The crack tip strain measurements can be used to determine crack tip creep rates during a creep-fatigue cycle. The results for both the strain measurements and the COD measurements showed that a positive slope existed over this 120 second period. The results shown herein are only for a very limited study, and it is expected that a greater understanding of the crack tip behavior could be gained by conducting these tests over many more cycles and different test conditions. Nevertheless these results suggest that creep and crack opening take place during the hold period studied for this material under these conditions and that they can be measured using the DIC system.

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References

[1] K.O. Findley, J.L. Evans, A. Saxena, A critical assessment of fatigue crack nucleation and growth models for Ni- and Ni,Fe-base superalloys, Int Mater Reviews, 25 (2011) 49-71.

[2] Evans, J.L. and Saxena, A., Elevated temperature crack growth rate model for Ni-base superalloys, in: Proceedings of the 12th International Conference on Fracture, Ottawa, Canada, July 12-17, 2009.

[3] J.L. Evans, Method for comparing the crack tip kinetics during creep-fatigue loading of nickel-base superalloys, Mater Sci Eng, A, 528 (2011) 5306-08.

[4] E. Andrieu, R. Molins, H. Ghonem, A. Pineau, Intergranular crack tip oxidation mechanism in a nickel-based superalloy. Mater Sci Eng A Struct Mater Prop Microstruct Process, A154 (1) (1992) 21-28.

[5] A. Pineau, S.D. Antolovich, High temperature fatigue of nickel-base superalloys – A review with special emphasis on deformation modes and oxidation, Eng Failure Analysis, 16 (2009) 2668-2697.

[6] D. Nowell, M.E. Kartal, P.F.P De Matos, Digital image correlation measurement of near-tip fatigue crack displacement fields: constant amplitude loading and load history effects, Fatigue Fract of Eng Mater Struct, 36 (2013) 3-13.

[7] G.J. Pataky, H. Sehitoglu, H.J. Maier, High temperature fatigue crack growth of Haynes 230. Mater Characterization, 75 (2013) 69-78.

[8] M.A. Sutton, J.J. Orteu, H. Schreier, Image Correlation for Shape, Motion and Deformation Measurements: Basic Concepts,Theory and Applications, Springer, New York, 2009.